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GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station

PROJECT INITIATION

Date: November 21, 1972

Project Title: Miniature Molecular Frequency Source

Project No.: A-1477

Project Director: Mr. J. J. Gallagher

Sponsor: U. S. Army Electronics Command; Fort Monmouth, New Jersey

Effective November 15, 1972 Estimated to run until: June 14, 1974 *

Type Agreement: Contract No. DAAB07-73-C-0065 Amount: $ 78,200.00

* Additional time for Final Reporting effort.

REPORTS REQUIRED: Monthly Cost Performance REports; Monthly Progress Letters, Interim Technical Report; Final Technical Report.

SPONSOR CONTACT PERSON:

Technical Matters
(Individual not named)
Semiconductor & Frequency Control Devices Area (AMSEL-TL-S)
U. S. Army Electronics Command
Fort Monmouth, New Jersey 07703

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(Thru GTRI)
Mr. R. J. Whitcomb
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Defense Priority Rating: DO-A7 under DMS Reg. 1.

Assigned to Special Techniques Division

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RA-62

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: April 26, 1976

Project Title: Miniature Molecular Frequency Source

Project No: A-1477

Project Director: Mr. J. J. Gallagher

Sponsor: U. S. Army Electronics Command; Ft. Monmouth, New Jersey

Effective Termination Date: 10/31/74 (Final Report sent 4/9/76)

Clearance of Accounting Charges: N/A all have cleared

Grant/Contract Closeout Actions Remaining: NONE

_ Final Invoice and Closing Documents
_ Final Fiscal Report
_ Final Report of Inventions
_ Govt. Property Inventory & Related Certificate
_ Classified Material Certificate
_ Other ______

Assigned to: Electromagnetics Laboratory (School/Laboratory)

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CA—4 (3/76)

A-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 1

Period Covered: 15 November 1972 to 15 December 1972

December 19, 1972

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the first month of this contract, preparations were made for the initial laboratory experiments on the stabilization of a CO_2 laser. Attendance at the Electron Devices Meeting has assisted in obtaining information important to the requirements of the contract. A technical conference with Dr. Eric Hafner, contract monitor, at Fort Monmouth has been held and has helped to establish priorities and goals for the contract.

2. Work Performed During the Month

Work has been started on preparing the apparatus necessary for the preliminary experiments on stabilization of the CO_2 laser. In order to perform some of the initial investigations of the characteristics of the laser and the Lamb dip control cell, a test bed is being constructed, and the associated vacuum equipment is being assembled for the CO_2 laser system. The test bed consists of two stainless steel plates for mounting laser mirrors, separated by 24 inch long invar rods. The invar rods measure 3/4 inch in diameter. The apparatus will be used for testing laser tubes from approximately 18 inches in length down to 2 inches in length. Both waveguide lasers and conventional lasers will be investigated. Sufficient space is provided within the resonator for the control cell. The stabilizing of the laser will be performed with the cell inside the resonator before performing investigations on external resonators.

A survey of vacuum apparatus available within the Engineering Experiment Station was made. Two types of vacuum systems are desired for this work. One will be necessary for the preliminary experiments for flowing gas mixtures and for some filling of static gas mixtures. The other system will be for the eventual filling of cells and laser tubes which will be sealed off. Sufficient equipment exists within our own group to assemble the first desired system, while several systems exist in the Physical Science Division which will fulfill the second need. Ray Hart has one clean system which would be particularly appropriate for this work. In addition, several mass spectrometer heads are available which can be used with these vacuum systems for analysis of the gas mixtures. One head which would be available for permanent use on our system requires some work on the electron multiplier.

The International Electron Devices Meeting provided information on several areas related to the contract. In particular, several details on the following subjects were discussed:

(1) Small waveguide lasers;

(2) Integrated optics;

(3) Electrode materials for sealed-off CO_2 lasers.

The waveguide laser would be a convenient device for applications as a miniature CO_2 laser, but at present, the power consumption of these lasers far exceeds the requirements for our system. On the order of 10-30 watts input power is required to operate these small diameter sources. Coupling into the lower order modes also presents a problem. An improvement in lowering the required current was reported in a paper on a CO waveguide laser. Reference was made to a paper by M. J. Posakony, "A High Voltage Current Regulator for Laser Gas Discharge Tubes," Rev. Sci. Instru. 43, 270 (1972).

The use of integrated optics will be considered during the course of this program, however, several problems were discussed at the Electron Devices Meeting. Coupling in and out of these elements could be a deterrent to their use in our systems.

The use of various materials for laser cathodes and the use of indium seals for sealed-off systems were discussed by V. Hochuli. We have written Hochuli for reports on his cold cathode investigations and have obtained a copy of the paper "Indium Sealing Techniques," by V. Hochuli and P. Haldemann, Rev. Sci. Instru. 43, 1088 (1972). These sealing methods are applicable to a variety of materials which we will use.

A discussion with Dr. Eric Hafner on December 8, 1972, provided the basis for the program to be followed. It was decided that the initial investigations should be performed on determining the use of a waveguide laser or a conventional short CO_2 laser and in investigating the characteristics of the control cell in the external configuration. Early determination of the techniques of establishing a standing wave in an external cell is considered important. A schedule of future technical discussions was set up with Dr. Hafner.

The use of ULE quartz, with a thermal expansion coefficient of $2 \times 10^{-8} ({}^{\circ}C^{-1})$, is being considered. Corning, manufacturers of this material, has been consulted, and Mr. Ed Phillips of the Corning, New York plant is sending us information on the properties and machining of the quartz.

An early determination of whether the metal-metal oxide detector is to be constructed by us or purchased from Custom Microwaves in Longmont, Colorado, is being made. Mr. Horvath of Custom Microwaves has indicated that the detector would cost approximately $500 with an additional $150 for a box of 12 whiskers. It is quite possible that the cost is less than we could do it, but, if we require any special changes in the design that Horvath uses, the price could go up.

We have prepared a tentative schedule of the topics which we consider important to the contract and will follow this schedule closely during the program. The schedule will be subject to change as the work and discussions progress. The schedules for each topic are attached for future reference.

3. Plans for the Next Month

During the next month, work will continue on the laboratory CO_2 laser. The ordering of materials will be completed and the laser test bed will be constructed. Work will continue on the vacuum system and the 4.3 μm detector. Preparation of the internal control cell and the power supply will be started. If materials are delivered during the month, the assembly of the laser tube and control cell will be started. The electronics required for the initial studies will be assembled. Internal modulation, probably on the piezoelectric element, will be started. The use of indium sealing techniques will be studied since the Brewster angle windows for the initial studies can be attached by these methods.

A summary of a paper will be prepared for submission to the Frequency Control Symposium by January 12, 1973. This will be based upon preliminary design considerations and the work to be performed by the June date of the symposium.

4. Travel

J. J. Gallagher and R. G. Shackelford attended the IEEE Electron Devices Meeting in Washington on December 4 and 5, 1972, and traveled to Fort Monmouth, N. J. for the initial contract discussion with Dr. Eric Hafner on December 8, 1972.

5. Fiscal Information

Fiscal information will be provided in the Cost and Performance Reports which will be submitted separately on the fifth of each month. This submittal date is compatible with the Georgia Tech preparation of fiscal reports.

A-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 2

Period Covered: 15 December 1972 to 15 January 1973

19 January 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, work continued on the CO_2 laser system for initial laboratory experiments. Preparations for the external control cell are beginning by considering the requirements for the phase modulator. An abstract was submitted for presentation at the Frequency Control Symposium in June.

2. Work Performed During the Month

During the past month, the major effort has been performed on the laboratory CO_2 laser which will be employed for the stabilization experiments. Components have been ordered, and construction of the apparatus is progressing. Several parts were already available in the laboratory for the apparatus.

For discussion purposes, reference is made to the schedule which was a part of the first monthly letter. Annotated copies of relevant schedule sheets are included in this report.

Invar rods have been delivered and are being employed in the construction of the laser test bed. The rods are two feet long and 7/8" in diameter. Three rods are used in the test bed. The rods terminate in two 1" thick aluminum plates. The mirror holders, which are mounted in the aluminum end plates, are two Trapel Model 603 mirror mounts which were already available in the laboratory. Inserts are being made to hold the output mirror and a piezoelectric element on which the back mirror will be mounted. The three rod configuration will facilitate the moving of the bed to different laser tubes. The laser bed should be completed by 22 January.

The piezoelectric mirror drive is a miniature element, ordered from Jodon. It will be delivered on 25 January. Both modulation and control signals can be applied to the element. If satisfactory in performance, the element is small enough to be used eventually in the deliverable lasers.

A germanium flat mirror, used on another CO_2 laser, can be used as the output mirror. The mirror has an antireflection coating but no reflective coating. The natural reflectivity of Ge, approximately 39%, serves as the resonator output mirror. A maximum reflecting mirror has been ordered from Valpey and will be delivered on 25 January. The substrate is fused silica, and the mirror, 1" in diameter, has a front surface radius of 1.0 meter.

Difficulty has been experienced in obtaining electrode material for CO_2. Several vendors were unsuccessfully contacted. Coherent Radiation has agreed to sell the anodes and cathodes used in their commercial CO_2 lasers, and Dave Johnson of Coherent is sending us a quote on these units. For the laser flow system, the glassblower, Don Lillie, could prepare electrodes, but, for nickel and other desirable electrodes, a further search of materials sources will be required.

The laser tubes, control cells and vacuum system have been designed and are under construction. It is anticipated that these parts will be completed by the first week in February. Most of the vacuum parts exist in the laboratory but some small adaptors are being constructed for assembly. Three laser tubes, 18" (15" between electrodes), 7" (4" electrode separation) and 5" (2" electrode separation) lengths, are being built. Brewster angle windows of Irtran 2 will be used. Three Irtran 2 windows have been ordered from Eastman Kodak and are due for delivery on 30 January. The internal control cell will be attached to the laser tube, separated by one common Irtran window. The 4.3 μm radiation will be viewed from a sapphire window in the control cell.

The detectors required for the 4.3 μm radiation have been reviewed and ordered from Optoelectronics in California. Several vendors were considered. Discussions with Bomes Engineering personnel, who market a pyroelectric detector, confirmed our conclusions that the pyroelectric detector will not be sensitive enough for the room temperature observations. Three detectors were ordered from Optoelectronics. An InSb photovoltaic cell, operative at $77^{\circ}K$, will provide us with the optimum sensitivity for initial observations and for external control cell investigations. It will serve as a standard for comparison at higher detector temperatures. Two PbSe detectors, one for room temperature use and one for use with a thermoelectric cooler, will be tested. The PbSe detectors will be delivered on 25 January, while the InSb unit is scheduled for delivery on 12 February. These detectors will be used with a narrow band filter, which has been received from Optical Coating Laboratories. The filter has a 0.42 μm half-bandwidth, 77% peak transmission, blocking capability out to 8.5 μm, is centered at 4.286 μm and is antireflection coated.

A trade-off between purchasing detector pre-amps (available from Barnes Engineering for $300) or building the units was investigated. It was decided that it is more economical to construct the pre-amps.

In order to modulate the piezoelectric element and to stabilize the laser, consideration has been given to building a lock-in amplifier, the dc amplifier, reference and servo-components. The estimated cost of $2500 and the time of completion were compared with the purchasing of a commercial stabilizer. Lansing sells a laser lock-in stabilizer for $1590, and it was decided to purchase this unit. Written permission to purchase this unit has been submitted. Delivery time is less than two weeks.

The existing power supply is undergoing a check-out to determine if further regulation is required for the laboratory experiments. The metal-metal oxide diode will be purchased from Custom Microwaves (E. Horvath) for both economical purposes and the experience of Horvath with diodes of this nature. Horvath and Ken Evenson at NBS have designed units which Horvath sells, but we will have to review these designs to assure that they are appropriate for our heterodyning experiments.

Investigations of the requirements on an external modulator when the control cell is moved outside the laser resonator have been started. Currently under study are the characteristics of GaAs as a phase modulator. Requirements on the frequency swing, the depth of modulation, crystal size and orientation, and power drive are being considered.

An abstract was submitted for consideration to be presented at the Frequency Control Symposium. The paper is intended to outline our program and to present the work accomplished to June.

3. Plans for the Next Month

During the next month, it is planned to complete the construction of the vacuum system, the laboratory laser devices and the associated electronic equipment. Experiments will be started on stabilization of the laser by the internal control cell. Analysis of the servo-control system will be initiated. Work related to waveguide lasers and to the external cell methods will be started. The requirements of the GaAs phase modulator will be established. J. Gallagher will join E. Hafner in a visit to MIT on February 8 and 9, to discuss stabilization methods with A. Javan and C. Freed.

A-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 3

Period Covered: 15 January 1973 to 14 February 1973

February 18, 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, construction of the major parts for the laboratory CO_2 laser system was completed, and assembly of the apparatus has started. Several components have been ordered and received. Necessary electronic parts are being constructed. The requirements for an external phase modulator are being investigated. An informative visit to Lincoln Lab and MIT was made; a report for this trip is included as part of this report.

2. Work Performed During the Month

During the past month, the major components for the vacuum system and CO_2 laser systems have been constructed. The metal parts have been completed and are being assembled. The vacuum system will be a combination of metal and glass components, advantage being taken of existing equipment. A Welch Model 1397B mechanical pump will be used for rough pumping and for the CO_2 laser flow system. A stainless steel chamber with appropriate valving is available for eventual use in filling sealed-off cells. This chamber will be pumped by an NRC Model 184 diffusion pump, supported by nitrogen trapping. Arrangements are being made for by-passing the large chamber for the laser flow systems. While the apparatus will not be as elegant as the equipment seen in the Freed/Javan laboratories, it will be useful for the variety of problems which must be considered in this program.

The glass-blower is completing the laser tubes and control cells. A delay was experienced in obtaining electrodes. Both anodes and cathodes were purchased from Coherent Radiation. The cathode is a nickel sheet connected to a tungsten rod while the anode is a small nickel cap connected to a tungsten rod. These will be satisfactory for a flow system, but, for sealed-off systems, highly pure nickel electrodes or an equivalent will have to be employed. Our glass-blower has indicated that he would have difficulty sealing nickel in glass. Consideration will be given to the in-line anodes as employed by Freed.

The glass control system will have to be provided with shielding and reflectors to provide a minimum radiation background for the 4.3 μm detector. Assembly of the glass system will be performed during the next week.

The CO_2 laser power supply is being checked out. Additional current regulation is necessary, and the parts have been ordered for this. These parts are scheduled for delivery on 20 February 1973.

A laser test bed, consisting of aluminum endplates and three invar rods, has been constructed and will be used with all laser tubes to be constructed. In addition, several parts have been received from vendors:

1. Three Irtran 2 windows (2 inch diameter, 0.068 inch thickness) to be used as Brewster angle windows were received from Eastman Kodak. Two others are available from previous CO_2 laser work. The Brewster angle window used by Freed between his laser and control cell is a barium fluoride window. The transmission of BaF_2 shows the material to be superior to Irtran 2, but it is more expensive. This material will be considered for use in future systems.

2. A maximum reflecting mirror at 10.6 μm has been received and will be used with a germanium flat which was already available in the laboratory. The germanium mirror will serve as the output mirror while the new mirror will be mounted on a piezoelectric driver, already received from Jodon. Tropel mirror mounts from previous work will be used.

3. Lead selenide and indium antimonide 4.3 μm detectors have been received from Optoelectronics. The indium antimonide detector will be used at 77°K while the lead selenide detectors will provide operation at room temperature and 190°K. A narrow band filter centered at 4.3 μm has been obtained from OCLI, and methods for cooling this filter will have to be developed. The window of the InSb detector appears to be coated, possibly having a filter built into the dewar. Further information will be necessary from Optoelectronics. Pre-amps for these detectors will be built. It is important for the photovoltaic InSb detector that provision be made to compensate for the self-bias of the device in order to maintain a constant detector bias.

4. A Lansing Model 80-214 Laser Lock-in Stabilizer has been received and will be used for controlling the feed-back signal. Provision exists for modulating the piezoelectric element, processing the detected signal and applying the correction signal to the mirror driver.

5. A SAT HgTe-Cd-Te detector has been received and will be used for detection of the 10.6 μm laser signal. It can in turn be employed for the heterodyning of two CO_2 lasers. For high sensitivity, a low input transformer can be used to match to an amplifying system, but a pre-amp with controlled bias will be necessary for broad-band operation.

During the past month, the requirements for phase-modulation have been studied and this work will continue in support of the external cell system.

3. Plans for the Next Month

During the next month, completion of the laboratory CO_2 system will occur. Initial experiments will start. For the first experiments with the control cell, detailed thermal shielding will be necessary. The external phase modulator, external control cell and waveguide laser will be subjects for study. In the light of the technical discussions with C. Freed and A. Javan, further information on large area detectors and arrays will be solicited from IR detector manufacturers.

TRIP REPORT

J. J. Gallagher
Boston, Massachusetts: Lincoln Lab and MIT
8-9 February 1973

A trip was arranged by Dr. Eric Hafner of ECOM to visit Dr. C. Freed at Lincoln Lab and Dr. Ali Javan at MIT to discuss the CO_2 laser stabilization techniques employed by Hafner and Javan. Originally, Dr. Hafner was to join J. J. Gallagher on this trip, but it was necessary for him to cancel his plans to do so.

The initial visit was with Dr. Freed on Thursday afternoon, February 8. This proved to be an enlightening visit as Freed was very informative and he showed several of the components used in his experiments. Both Freed and Javan believe the proposed work can be performed, but both in turn had reservations about the use of room temperature detectors at 4.3 μm.

Several factors were discussed with both Freed and Javan, and among the most important were the following:

1. Freed was mainly concerned about the detectors for the 4.3 μm fluorescence cell. He indicated several aspects which were not evident in the original Freed-Javan paper. In particular, he found that even the cooled InSb detector (77°K) had difficulty initially in detecting the fluorescence since a considerable amount of radiation background exists and can swamp out the desired signal. The detectors are definitely background limited. Freed stated that the radiation which affects the detector is <u>not</u> just from the 4.3 μm region but covers practically the entire spectrum. In order to alleviate the problem, Freed arranged for the detector to see a cooled background. A mirror is placed at the bottom of the control cell so that the detector sees itself, while cooled shielding is used around the detector.

Freed indicated that he gave NBS a seminar discussion on the stabilization technique, and it was only with difficulty that NBS finally got the system working with a cooled detector.

Freed's detectors were made by Texas Instruments and have cooled filters internal to the dewar. He emphasized the need for stable bias as the noise level varies as a function of the bias. The need for large area detectors is evident. Most IR detectors are small area configurations. Freed used detectors with element areas on the order of 2 mm x 2 mm, but he had TI build him a detector 1/2-inch x 1/2-inch. He has not used this device as yet but the TI people have told him that the bigger elements do not buy much as the noise goes up considerably. Javan disagrees with this and is convinced that the signal-to-noise improves by the square root of the area. Freed's interest in bigger room temperature detectors also seems to contradict the statements about the lack of gain from increased areas.

We discussed methods of enhancing the signal with room temperature detectors. Freed mentioned that he has discussed various possibilities with Santa Barbara Research and indicated that the idea, which we have discussed with Dr. Hafner, of using a control cell coated with stripes of PbSe to increase the area of the detector should be pursued further.

2. We discussed the use of an external control cell which Freed is presently making up. He said that the Lamb dip could be achieved by a single reflection back through the cell. The next day, Javan showed me an external cell which he said he has used. This cell had flat windows and appeared to be a single reflection cell. Javan has used modulation internal to the laser cavity for this application.

Freed indicated that saturation of the control cell signal presents a problem for an internal cell, but expressed concern that insufficient power would be available to use with an external cell. The cell that he envisions using would be of a large diameter, as is Javan's, and would require defocusing of the small 2-3 mm diameter laser beam.

3. All of Freed's lasers are very well designed and probably expensive. He uses a modular concept so that parts can be interchanged. He provided us with a reprint of his paper given at Quebec in 1971, and this describes many of the details of his devices. Among the items of interest are his use of high vacuum valves and a large reservoir for sealed-off systems, in-line anodes which do limit the active discharge region but keep the mirrors free of discharge effects, the use of bellows and mirrors internal

to the laser avoiding the requirement of Brewster's angle windows. He uses a small John Fluke Model 415 power supply for his small ($\leq$ 18 inch) lasers.

4. On February 9, J. Gallagher visited Ali Javan's laboratory and had a long discussion with him. Freed, who originally planned on visiting Javan with us, felt that we had covered most of the topics of importance and did not attend the sessions with Javan. Javan reiterated most of Freed's statements, emphasizing the need for 4.3 μm detectors. He is confident that the miniature system can be built but indicated that more detector work, possibly working closely with a detector manufacturer, is necessary. Javan, in need of greater sensitivity and more narrow lines, is going to helium cooled detectors. He uses the stabilization system with several laser systems now. We toured Javan's lab seeing most of the experiments that he has going.

Both Javan and Freed were very helpful and extended an offer of any further assistance which they can provide. The emphasis on 4.3 μm detectors and power limitations with external cells appear to be the most significant factors for consideration in a miniature version of their stabilization system.

A-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 4

Period Covered: 15 February 1973 to 14 March 1973

March 19, 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. SUMMARY

During the past month, assembly of the apparatus for laboratory testing of CO_2 lasers has continued. The requirements for an external phase modulator have been investigated. Consideration is being given to a small sealed-off laser. A review of the program was held with Dr. E. Hafner, Contract Technical Monitor, who visited the laboratory on March 14, 1973.

2. WORK PERFORMED DURING THE MONTH

During the past month, the assembly of the vacuum system for laboratory testing of CO_2 lasers has continued and is nearing completion. Availability of machined parts and the glassblower's time has delayed the completion beyond the scheduled date. Provision is being made for using the lasers in both flow systems and in sealed-off operation. For the optimum conditions in sealing off lasers, vacuum systems in the Physical Science Division can be used.

The initial experiments will use a 15-inch laser with a 5½ inch fluorescence control cell for the purpose of observing the Freed-Javan 4.3 μm stabilization.

During the month, the use of an external electro-optic phase-modulator was investigated. The two materials which are most appropriate for a 10.6 μm modulator are GaAs and CdTe, both of which are expensive materials. From Appendix I, it is seen that, in the operation of a phase modulator, there is a trade-off between the modulating voltage and the modulation frequency. If it is required to modulate the 10.6 μm signal over the frequency width of the discriminator (~0.66 MHz), the modulation frequency is high, 10 MHz for GaAs and 5 MHz for CdTe, in order to maintain a relatively low modulation voltage of 300 volts across a 3 mm crystal. If one only has to modulate over a 1 kHz bandwidth, the modulation frequency drops considerably (to 14 kHz and 7 kHz, respectively, for GaAs and CdTe) for the same voltage. While the power consumed in the electro-optic crystal is low in each case, the power requirements to generate the modulation voltages would be impractical for our small devices.

In discussions with Dr. Hafner, it was decided to consider the techniques of modulation by moving an external mirror. Recently, Goldberg and Yusek used this technique in a CO_2 laser system with a cell of SF_6 external to the laser (Reference 1). They showed the advantages of the external modulation as removing the dependence of the inverted Lamb dip position on laser characteristics.

With respect to the use of an external control cell, Goldberg and Yusek, and Rabinowitz, et al (Reference 2) have both used external SF_6 absorption cells. They have indicated that the double pass cells do not have standing wave structures since the CO_2 laser/SF_6 absorption interaction is sufficiently strong to observe the Lamp dip. The arrangement in turn separates the return beam from the incident beam thus avoiding feedback to the laser.

The use of the external modulated mirror would allow modulation of sufficient magnitude to achieve optimum signal-to-noise with the external detector and control cell.

During Dr. Hafner's visit to the Station, the following points were discussed:

1) The thermal shielding required for the InSb detector. In order to provide a background on the order of $77^{\circ}K$, the construction of a shield with control cell, mirror and 4.3 μm filter was discussed. This shield is presently being constructed.

2) The use of a sealed-off ULE laser was discussed. A design similar to that of Hochuli (Reference 3) seems appropriate for the small laser required for our project. Following the discussion with Dr. Hafner, inquiries were made concerning the construction of such an instrument. Appendix 2 gives notes on discussions of this item. The device being considered is a two inch long, 6 mm bore laser cut out of a two inch diameter block of ULE quartz. Quotes are presently being sought from the vendors given in Appendix 2.

3) The use of arrays of PbSe detectors was discussed. A design involving a ULE quartz body is being considered. B. Livesay of the Physical Sciences Division is reviewing the literature to determine if this can be done at the Station. Letters will be issued to detector manufacturers to obtain quotes and information on the possibilities of large detector arrays.

4) In order to provide information on the anticipated signal strength and modulation requirements, the calculation of the intensity of the 4.3 μm radiation will be undertaken. This will include determination of the population change of the energy levels under 10.6 μm radiation, the background radiation at 4.3 μm, characteristics of the 4.3 μm and the modulation bandwidth as a function of the S/N. Dr. Hafner indicated that probably Jim Barnes has considered this problem during the past year.

A current regulator has been added to the existing power supply during the past month. In addition, pre-amps are being constructed for the PbSe detectors. The pre-amps for the InSb detector and the HgTe-CdTe detectors are being purchased, on internal funding, from Perry Amplifier.

3. PLANS FOR THE NEXT MONTH

During the next month, the final assembly of the laboratory laser will be completed and the initial stabilization of the laser will be studied. The small stable laser will be investigated as will the use of an external mirror modulator and the external control cell. Detector arrays will be further studied with information solicited from manufacturers. It is planned to visit U. Hochuli at University of Maryland during the week of March 26 to discuss the small, stable laser activities in which he is involved. The calculation of the 4.3 μm signal strength will be performed.

REFERENCES

1. M. W. Goldberg and R. Yusek, Appl. Phys. Letter 18, 135 (1971).

2. P. Rabinowitz, R. Keller and J. T. LaTourrette, Appl. Phys. Letter 14, 376 (1969).

3. V. Hachuli and P. Haldemann, IEEE Journ. Quant. Elec. QE-7, 573 (1971).

Appendix 1

Electro-Optic Phase Modulator for 10.6 μm Laser

The phase modulated wave is given by (Reference 1):

$$e(t) = E_c \sin [\omega_c t + k_p e_m(t) + \theta_o] \tag{1}$$

where E_c = carrier amplitude,

ω_c = angular frequency of carrier,

$$k_p = \frac{\theta_d}{E_m} = \frac{\text{maximum phase deviation}}{\text{amplitude of signal}}, \tag{2}$$

$e_m(t)$ = modulation signal,

θ_o = constant, arbitrary phase.

The instantaneous angular frequency of e(t) is (Reference 2):

$$\omega_i = \frac{d\,\varphi\,(t)}{dt} = 2\pi\ f_i, \tag{3}$$

where $$\varphi\,(t) = \omega_c t + k_p e_m(t) + \theta_o, \tag{4}$$

= instantaneous phase of e(t) above.

Then,

$$\frac{d\,\varphi\,(t)}{dt} = \omega_c + k_p \frac{de_m}{dt}, \tag{5}$$

but,

$$\omega_i = \omega_c + \Delta\,\omega_i \tag{6}$$

so that

$$\Delta\,\omega_i = k_p \frac{de_m}{dt} = 2\pi\ \Delta\ f_i. \tag{7}$$

By (2) above,

$$k_p = \theta_d/E_m.$$

The phase shift introduced by the modulator is (Reference 3):

$$\Gamma = \frac{\pi L n_o^3 r_{41} E_z}{\lambda}, \tag{8}$$

where L = length of crystal,

n_o^3 = modulator refractive index = 3.34 for GaAs,

r_{41} = electro-optic coefficient

= 1.6×10^{-10} cm/volt for GaAs,

E_z = transverse electric field,

λ = wavelength = 10.6 μm in our case.

Then,

$$k_p = \frac{\Gamma}{E_z} = \frac{\theta_d}{E_m} \tag{9}$$

and, by (7) above,

$$2\pi \Delta f_i = \frac{\Gamma}{E_z} \frac{de_m}{dt}$$

or,

$$2\pi \Delta f_i = \frac{\pi L n_o^3 r_{41}}{\lambda} \frac{de_m}{dt} \tag{10}$$

$$\frac{de_m}{dt} = \frac{2 \lambda \Delta f_i}{L n_o^3 r_{41}} .$$

The materials for modulating the CO_2 laser are GaAs and CdTe. Examples for these two materials can be given.

EXAMPLE 1: For GaAs, consider the case of the frequency Δf_i being 0.66 MHz, which is the frequency spread between the inflection points of the 4.3 μm derivative of the original Freed-Javan paper (Reference 4). Consider the case of the GaAs crystal dimensions being 3 mm x 3 mm x 4 cm, with the signal propagating along the 4 cm length.

For $\lambda = 10.6\ \mu m$ (= 1.06×10^{-3} cm),

$$\left.\frac{de}{dt}\right|_{max} = \frac{2(1.06 \times 10^{-3}) \times 6.6 \times 10^{5}}{4 \times (3.34)^{3} \times 1.6 \times 10^{-10}}$$

$$= 5.86 \times 10^{10}\ \frac{v/cm}{sec}\ .$$

For $e_m = E_m \sin \omega_m t$,

$$\frac{de_m}{dt} = \omega_m E_m \cos \omega_m t$$

$$\left.\frac{de_m}{dt}\right|_{max} = \omega_m E_m = 5.86 \times 10^{10}\ \frac{v/cm}{sec}\ .$$

For $E_m = 10^3$ v/cm = 300 volts/0.3 cm,

$$\omega_m = 5.86 \times 10^{7}\ \text{Hz}$$

or

$$f_m \doteq 10\ \text{MHz}$$

EXAMPLE 2: For CdTe,

$$\frac{de_m}{dt} = \frac{2\ \lambda\ \Delta\ f_i}{L\ n_o^3\ r_{41}}\ .$$

The figure of merit, $n_o^3\ r_{41}$, is larger for CdTe than for GaAs (Reference 5):

$$n_o^3\ r_{41} = 12 \times 10^{-9}\ \text{cm/v for CdTe}$$

$$= 6 \times 10^{-9}\ \text{cm/v for GaAs}$$

so that

$$\left.\frac{de_m}{dt}\right|_{CdTe} \approx \frac{1}{2} \left.\frac{de_m}{dt}\right|_{GaAs}$$

$$\approx 3 \times 10^{10} \, \frac{v/cm}{sec} ,$$

so, $f_m \approx 5$ MHz for $e_m = E_m \sin \omega t$

$$\text{and } E_m = \frac{300 \text{ v}}{0.3 \text{ cm}} .$$

The modulation index in this case is $\frac{\Delta f_i}{f_m} = 0.13$. The absorption loss in CdTe is much less than for GaAs.

If it is only necessary to modulate the frequency of the signal over a band of 1 kHz, i.e.,

$$\Delta f_i \cong 1 \text{ kHz},$$

then,

$$\left.\frac{de_m}{dt}\right|_{max} = \frac{5.86 \times 10^{10} \times 10^3}{6.6 \times 10^5}$$

$$= 8.88 \times 10^7 \text{ v/sec}.$$

For $E_m = 10^3$ v/cm,

$$\omega = \frac{8.88 \times 10^7}{10^3} = 2\pi f_m$$

or,

$$f_m = 1.41 \times 10^4 \text{ Hz for GaAs}$$

$$= 7 \times 10^3 \text{ Hz for CdTe}.$$

The power required for these modulators can be calculated from considering the modulator as a resonant circuit (Reference 3). When this is done, the power required for the $\Delta f_i = 0.66$ MHz case is:

for CdTe,

$$P = 0.48 \text{ watts},$$

for GaAs,

$$P = 0.76 \text{ watts}.$$

In both cases, the modulation voltage was 300 volts.

REFERENCES

1. S. Seely, "Electron Tube Circuits," p.609.
2. B.P. Lathi, "An Introduction to Random Signals and Communication Theory," p. 351.
3. A Yario, "Introduction to Optical Electronics," Chapter 9.
4. C. Freed and A. Javan, Appl, Phys, Letter 17, 53 (1970).

Appendix 2

Notes on Small Stable Laser

The Corning Glass Works, manufacturers of ULE Quartz, referred us to Mr. Robert Chipley (203-677-4081, x652) of Hamilton Standards Division, United Aircraft Corporation, 1690 New Britain Avenue, Farmington, Conn., for information on the machining of ULE Quartz. Mr. Chipley was very helpful and indicated that the particular cavity that we wanted to fabricate was an easy job. He has been machining small holes (~ 0.100 inch) through 11 - 13 inch lengths of the material. He made a ring laser for Hochuli at Maryland but did not bid on the He-Ne laser that Hochuli has had constructed.

Mr. Chipley indicated that he could do the job and would inquire of his superiors if they would permit him to do so or if they would give us a quote on the job. He indicated that the machining of the annular grooves is no problem, but that the 0.250" hole is the most difficult part. The old ultrasonic techniques would give a 0.005" taper over a 2 inch length, but he now uses a Branson Ultrasonic Drill which apparently corrects for this problem.

Mr. Chipley indicated that a dust results from the machining of the quartz and that effort should be exerted to lessen this effect. He recommended that we have the bores given a commercial polish. It was indicated that the following organizations are also capable of machining the cavity we desire:

Bond Research Laboratories, Inc.
Bond Optics Division
Etna Road
Lebanon, New Hampshire 03766
(603) 448-2300

Dell Optics Company
9226 Kennedy Boulevard
North Bergen, New Jersey 07047
(201) 869-7300

Woodbury Glass
East Hartford, Connecticut
(Tim Sullivan is the contact)

Chipley indicated if Sullivan at Woodbury Glass stated that he could not do 2" deep 0.250 inch diameter hole, then he (Chipley) would do it for Sullivan.

Harold Bassett recommended Quartzite Processing, Incorporated, 6 Holyoke Street, Malden, Massachusetts 02148, (617) 322-1380, who have done work on silica for him. Mr. J. H. Westerman is the contact at Quartzite.

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MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 5

Period Covered: 15 March 1973 to 15 April 1973

April 23, 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, the laboratory laser was assembled and initial experimentation started. A stainless steel fluorescence control cell was constructed with cooling arrangements. A small CO_2 laser design has been made, and requests are being sent to optical houses for quotes. A layout of PbSe detector arrays has been made and this will be sent to detector manufacturers. A short visit was made during the month to the laboratory of Dr. Hochuli at University of Maryland. Calculations of the 4.3 μm signal strength have been started.

2. Work Performed During the Month

Following the discussion with Dr. Hafner on the construction of cooling mechanisms for the 4.3 μm control cell, a stainless steel cell was constructed. This chamber has a mirror at the bottom to reflect the cooled InSb detector. An arrangement has been designed and constructed to cool the 4.3 μm filter and surrounding environment with the exception of the CO_2 cell. This cell and the CO_2 laser have been connected by an Irtran 2 Brewster angle window, and the assembly has been connected to the vacuum system. Initial lasing investigations have started.

In order to investigate the small sealed-off laser system, a ULE quartz laser has been drawn up. This device is similar to that used by Hochuli for He-Ne lasers. The sketches of the three parts of the laser are attached to this letter. The main body will be 2 inches long and 2 inches in diameter. A 6 mm bore will be the laser tube, and annular cavities will hold the electrodes and also serve as gas ballast chambers. The two end plates will be constructed of ULE quartz. One will have a small ½ inch diameter area serving as a 4.00 radius of curvature reflector. The other will have a recessed hole to hold a Ge output mirror. These sketches are being sent to various optical houses for quotes. The cells will be sealed with indium solder as Hochuli has done.

Consideration is being given to arrays of PbSe detectors for the external control cell. We are seeking advice on these devices from detector manufacturers. A sketch of the type of arrangement that we would desire is attached. This consists of a 2 inch by 1 inch sapphire substrate which would serve as a side of the external control cell. There would be four sides like this. The detector area under this arrangement would be 3.6 in^2, compared to the 2 mm by 2 mm area of the InSb detector. This is a factor of 562 in area or 23.7 in the linear dimensions. Possibly the electrode width can be reduced allowing an increase in the detector area. This sketch will be sent to detector manufacturers for information and quotes. The back surface of the sapphire substrate will require a 4.3 μm filter. Information on the pre-amp requirements will also be sought.

On a recent trip to the Washington, D. C., area, a visit was made to the laboratory of Dr. U. Hochuli at University of Maryland. Hochuli provided some information on sealing-off of lasers. His effort has been mainly with He-Ne systems, although he has a large CO_2 laser report which will be available soon. This work is a detailed study of the materials for CO_2 lasers.

A current regulator has been constructed for the laser power supply and this is operating satisfactorily. A John Fluke Model 415A supply, which is used by Freed for his CO_2 laser work, has been purchased on internal funds and will be available in May. The pre-amps for the PbSe detectors are completed and are undergoing tests with the detectors. Pre-amps for the InSb and the HgCd-HgTe detectors have been ordered from Perry Amplifier and are due for delivery.

The calculation of 4.3 μm radiation from a room temperature control cell is being studied. The mechanism for excitation of the 4.3 μm fluorescence by 10.5 μm laser radiation is under investigation. The transfer of the saturation effects is not presented in detail in the literature, and we are presently studying this. It is expected that this calculation will be completed during the next month.

3. Plans for the Next Month

During the next month, the observations with the laboratory laser will be made and locking to the internal control cell with the InSb detector investigated. Several other investigations which are underway will be continued:

(1) Quotes and information will be sought from optical and detector manufacturers;

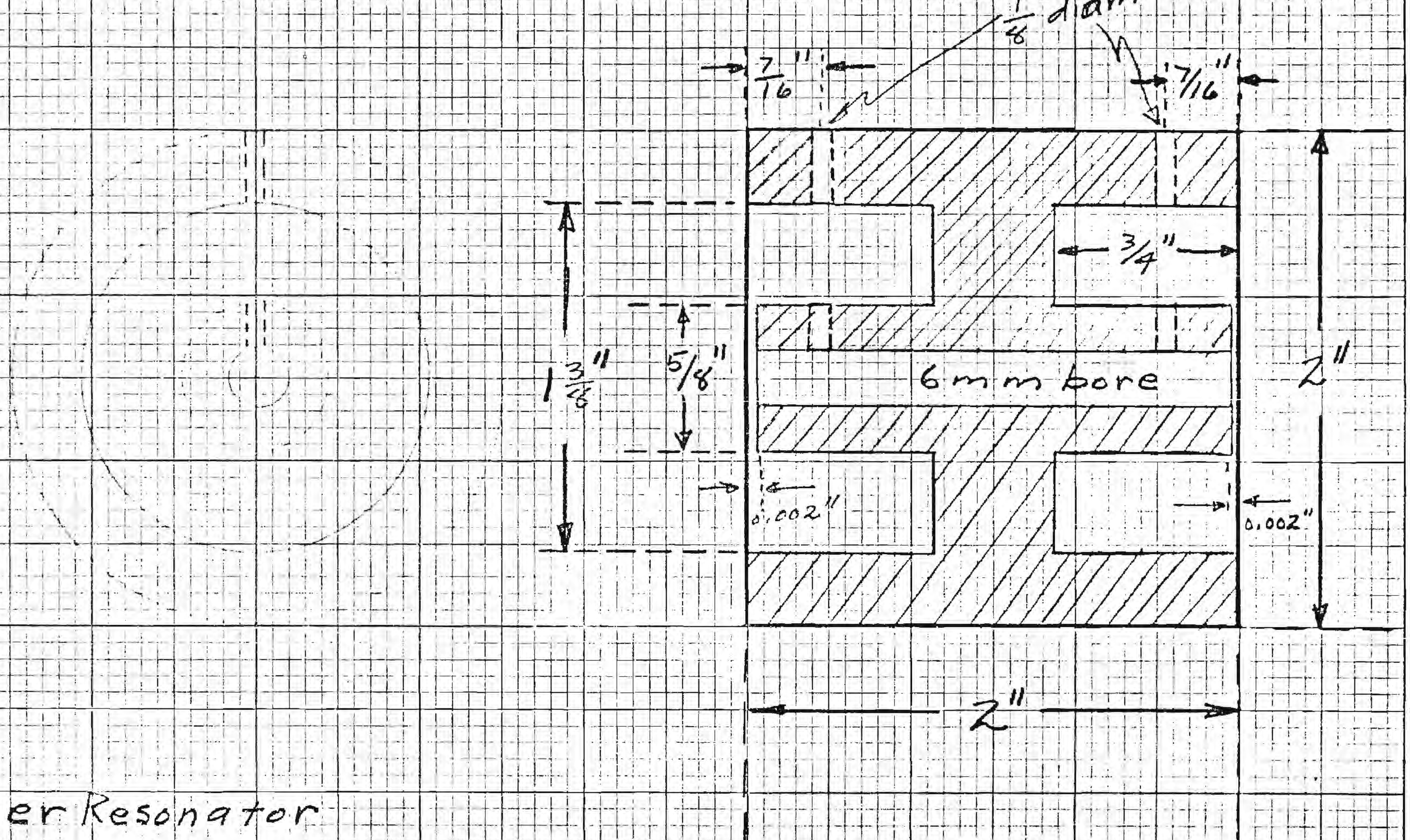
(2) Detector sensitivities will be checked;

(3) Sealing techniques with In solder will be studied;

(4) The method of external Doppler dither will be investigated; and

(5) The calculation of the 4.3 μm fluorescence and signal strength will be completed.

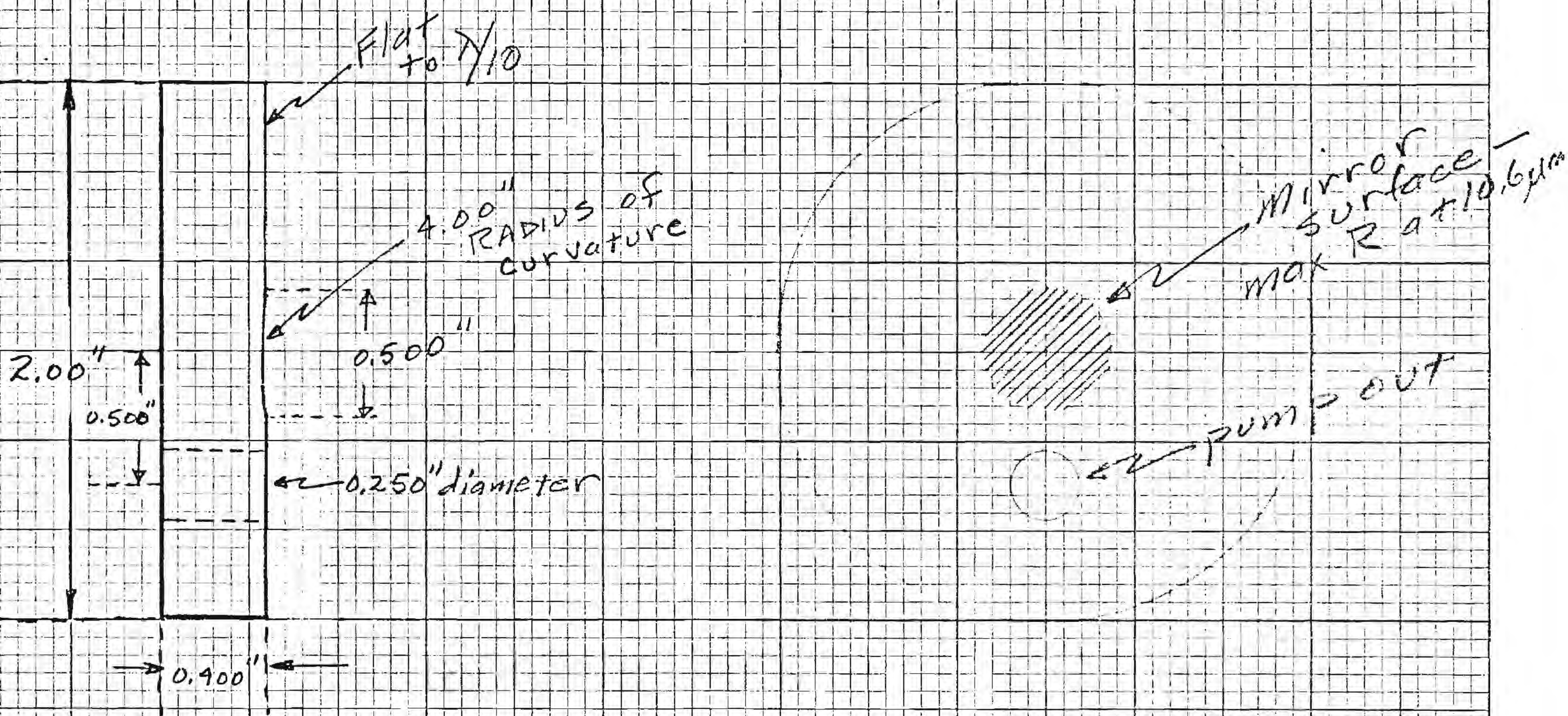
1



CO_2 Laser Resonator

Material: ULE Quartz
ENDS Flat and parallel to λ/10

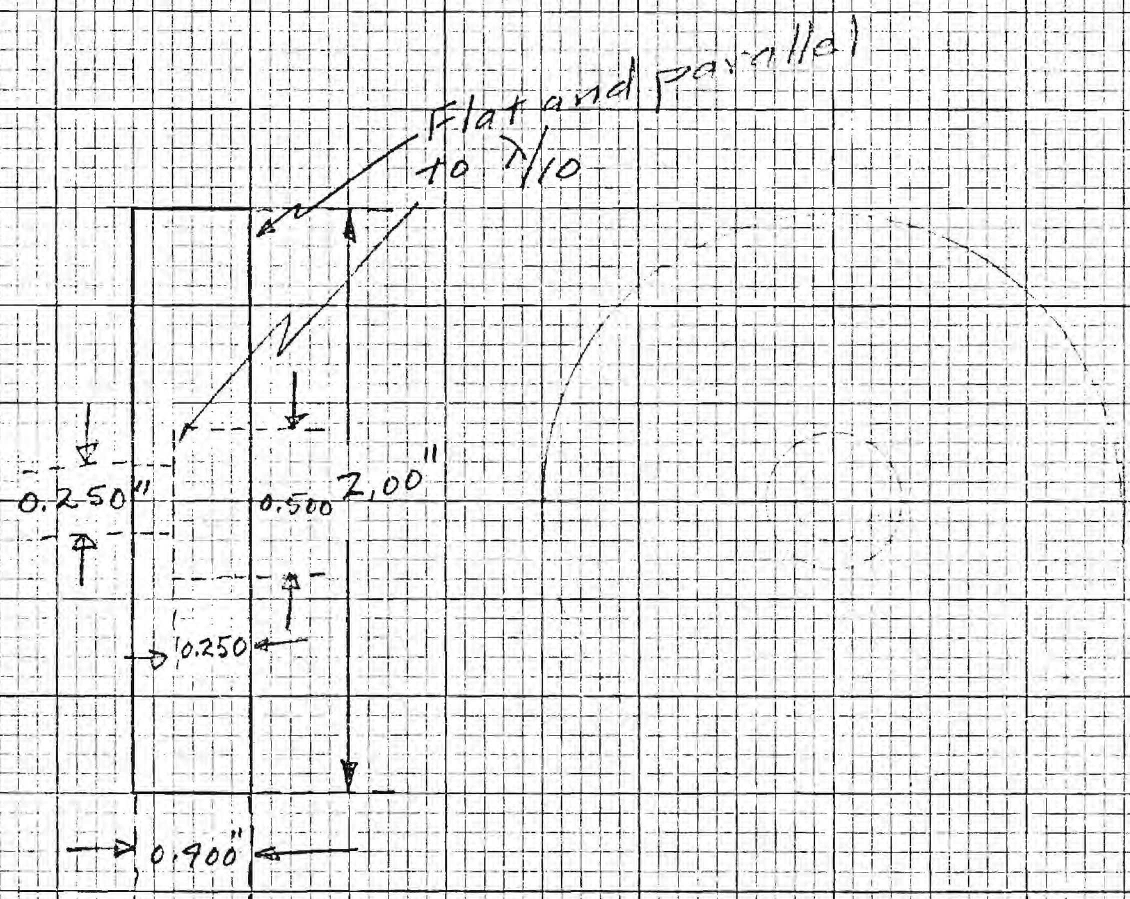
②

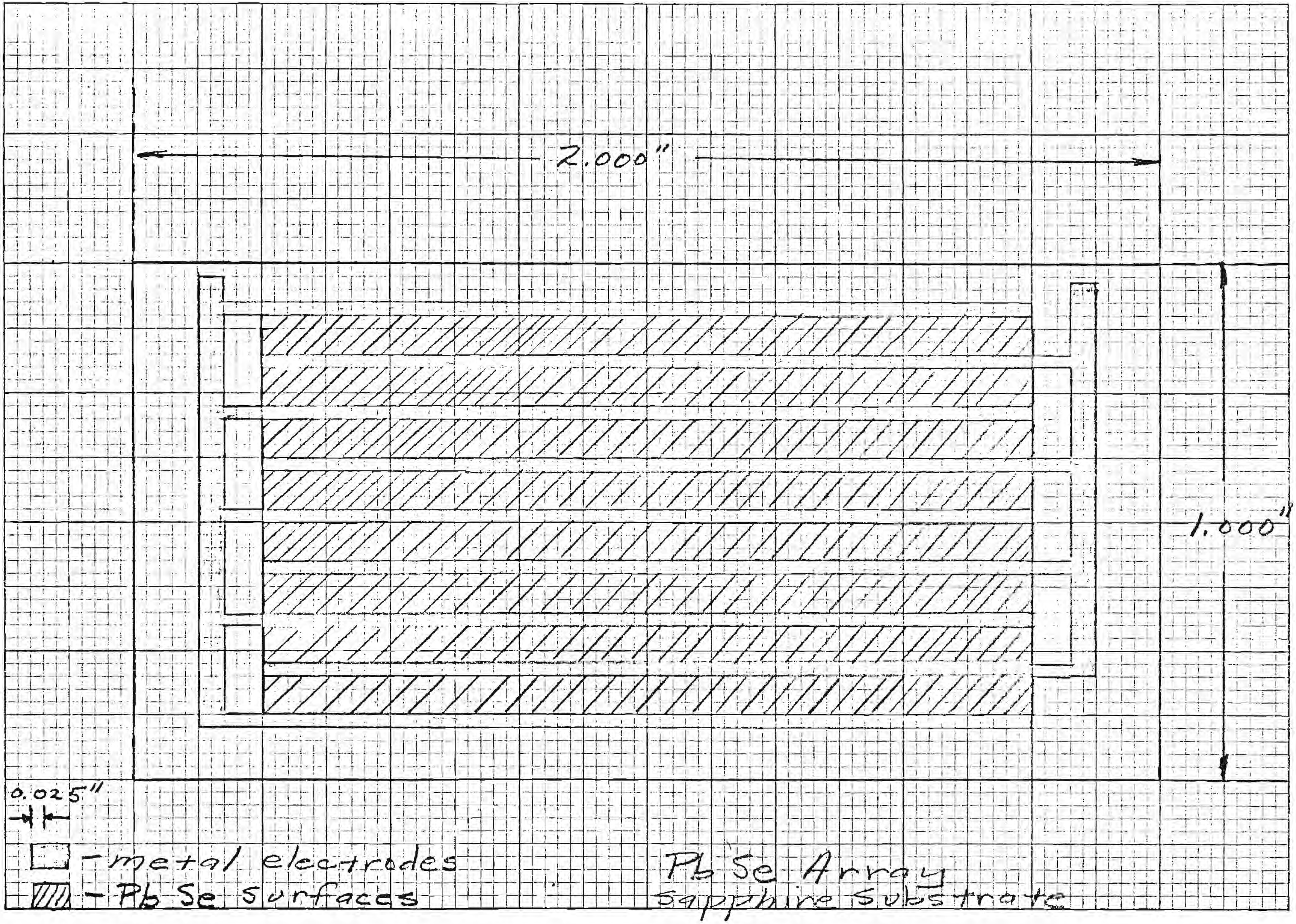


CO_2 Laser Reflector: small mirror area, 0.500" diameter with 4.00" radius of curvature; max reflectivity at 10.6 μm.

GE Quartz 0.250" diameter pump out

③





2.000"
1.000"
0.025"
- metal electrodes
- Pb Se surfaces
Pb Se Array
Sapphire Substrate

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MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 6

Period Covered: 15 April 1973 to 15 May 1973

May 23, 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, the construction of the laboratory laser and control cell has been completed, and initial experiments with the laser have been performed. Calculations of the 4.3 μm signal strength have been continued. Investigations have continued on the small sealed-off stable source and the external modulator/control cell configuration.

2. Work Performed During the Month

During the past month, construction of the laboratory CO_2 laser and the fluorescence control cell were completed, and initial investigations have been performed. The overall vacuum system operates down to 5×10^{-7} torr without cryogenic trapping and into the 10^{-8} torr region with trapping. During the initial laser investigations, minor vacuum problems and some power supply instability have been noted. These are being corrected so that stabilization studies will begin during the next month. The necessary pre-amps have been received for the 4.3 μm In Sb detector and the 10.6 μm HgCdTe detector.

The calculations on the signal at 4.3 μm are continuing. Further information on the effects of relaxation processes and the energy exchange mechanism is being sought. It is anticipated that these determinations will be completed during the next month.

Quotes have been sought from 10 optical apparatus vendors on the construction of a ULE quartz resonator. Thus far, 5 "no-bids" have been received and one quote has been received from Bond Optics. The total resonator cost is high ($1025) and further quotes are being sought. Capabilities for machining ULE Quartz in the Materials Division of the Station are being investigated. Samples of fused quartz have been drilled with a rotary burr. It appears that this technique will allow the machining of some required parts. Further checks with the Corning Glass Advanced Products Department indicate that they will do relatively simple drilling of the material, and quotes are presently being sought from them.

For the 4.3 μm detector array, Infrared Industries and Optoelectronics have responded that they can construct these elements and will submit quotes.

Investigations have continued on the use of an external modulator. For the use of a Doppler dither technique, a mirror system employing a piezoelectric drive has been considered. Most piezoelectric drives of a convenient size are limited to approximately 15 μm displacement. It is estimated that, for a modulation frequency of 520 Hz, a displacement of 1.26 mm is necessary to achieve a frequency sweep of 0.65 MHz. Higher modulation frequencies will allow the use of smaller displacements, but resonances within the PZT elements will have to be avoided or used. Drive power for the higher frequencies will have to be studied. Past investigators have employed mirrors driven by solenoids, but the power consumption is unfavorable for our use. Tuning forks (by Bulova) are used as choppers and have displacements of several millimeters. We are looking into the power consumption in these instruments.

Investigations are starting on the sealing techniques for the small laser, and versions of these small sources will be constructed when the ULE quartz resonators are available. Prof. Hochuli of University of Maryland has kindly forwarded us a rough copy of his report on CO_2 cathode materials, which will be helpful in this work.

3. Plans for Next Month

The laser tests and frequency stabilization studies will be performed during the next month. In addition, the following program items will be carried out:

1. Completion of the 4.3 μm radiation calculations.
2. In-house fabrication of ULE Quartz resonators.
3. Decision on quotes for ULE Quartz resonator purchases.
4. Decision on quotes for 4.3 μm detector arrays.
5. Completion of external modulator search and initial experiments on the system considered most appropriate.
6. Development of optimum sealing methods and initial seal-off experiments.
7. Review of program with Dr. Hafner during week of June 11.
8. Attendance at Frequency Control Symposium.
9. Preparation of first Interim Technical Report.

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 7

Period Covered: 15 June 1973 to 15 July 1973

19 July 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

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Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 8

Period Covered: 15 July 1973 to 15 August 1973

22 August 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, work has continued on a 200 Hz modulator. A cell for external fluorescence investigations has been constructed. Two laser cells have been received from Labglass. Preparations are being made for the assembling of a prototype system employing the sealed-off ULE quartz CO_2 laser.

2. Work Performed During the Month

Investigations have been performed on a 200 Hz external modulator. The most satisfactory device used thus far has been a stripped down miniature speaker. Despite its characteristics of providing sufficient amplitude at 200 Hz with low power consumption, a lack of symmetry in the speaker's construction causes an undesirable wobble of the mirror which results in a smearing of the incident signal. Contact has been made with the Massa Corporation which manufactures sonic equipment. They indicated that none of their units would meet our requirements, but referred us to small transducers made by Knowles in Chicago. A review of Knowles' literature does not indicate that their units will provide sufficient displacements. A piezoelectric bimorph has been sent to us by Gulton Industries, Inc., and the initial tests on this element have not shown sufficient displacements at 200 Hz. A device employing a rod moved by a small electromagnet is being fabricated in an effort to maintain alignment of the moving element.

A discussion with T. W. Meyer, of Lawrence Laboratory at Livermore, California, who has been performing saturation investigations of CO_2, indicated that a resonator is not required for fluorescence observations external to the laser. A standing wave provided by a single reflection has been used by Meyer. On this basis, an external cell has been constructed from an Invar block. Provision is made for mounting a single mirror on the rear of the cell or it can be converted to a resonator if this is later found to be necessary. It will initially be used with an InSb detector but a side can be opened to use a string of room temperature

PbSe detectors. The internal surface is cylindrical and is to be polished and gold plated to provide collection of the fluorescent signal. The cell will eventually be used with the sealed-off stable CO_2 laser.

During the month, two small (~ 18" long) lasers were received from Labglass. One of these is being connected up with the internal fluorescence cell so that the 4.3 μm tests can be performed both internally and externally. The internal cell-laser combination will employ only one salt window, that which separates the cell and laser. Approximately 1.5 watts are available from the existing 18 inch laser, and this apparatus will be used for fluorescence observations from the external control cell.

A tentative design of the prototype system has been made, and the components (modulator, external cell, and sealed-laser) should be available for assembling in late September. Other items considered during the month include:

(1) The room temperature PbSe detector array is still under study. Optoelectronics has put a quote in the mail (8/21/73) with a recommended design. They will quote for one side and all four sides of the control cell chamber.

(2) The ULE quartz resonator is scheduled for delivery at the end of August. Work is being performed on the sealing techniques in preparation for this apparatus. A furnace, capable of attaining 2000°F, has been installed. A 2 liter sample of Xenon has been obtained for filling of the resonator.

(3) Delivery of ULE quartz tubes for sealing and operation testing is overdue from Corning. These items are apparently delayed by Corning's vacation schedule.

(4) Consideration has been given to a BeO laser tube if the ULE quartz cannot dissipate the heat properly. National Beryllia and Consolidated Ceramics have been contacted. Both will make tubes at a high cost, but Consolidated often carries miscellaneous sizes that we might find to our specifications.

(5) Ray-tracing techniques have been considered for optimizing the collection optics for the external cell. Other than relatively simple, and not very conclusive, calculations, a determination by these methods would be time consuming and more costly than the program can afford at this time. Integrating spheres are presently being studied.

3. Plans for Next Month

The ULE quartz resonator should be available during the next month, and the laser will be assembled at this time. A finished version of the modulator is expected to be available in September. Fluorescence with both internal and external resonators will be studied. Assembling of the first prototype system will be started.

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MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 9

Period Covered: 15 August 1973 to 15 September 1973

28 September 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, power improvement of an eighteen inch long laboratory CO_2 laser has been made. An external fluorescence control cell is nearing completion. A fifteen inch CO_2 laser with internal control cell has been assembled and is under-going initial tests. ULE quartz tubes have been received from Corning and are presently being optically polished for construction of small CO_2 laser tubes. Sealing-off techniques are being investigated.

2. Work Performed During the Month

A small CO_2 laser, obtained from Labglass, has been improved in its power output by employing an output mirror with increased reflectivity. Previous operation has yielded approximately 1 watt with uncoated germanium windows ($\sim$ 37% reflectivity). With a hole coupled output mirror, the power output is approximately 3.5 watts. Much higher reflectivity than we have been using is desirable with the small lasers. This laser will be employed for studies with the external fluorescence cell.

An external fluorescence cell has been machined and internally polished. The inner cylinder is being gold-plated for reflection of the 4.3 μm fluorescence to the detectors. A single back mirror will be employed to set up the required standing wave in the cell. Initially a sodium chloride window will be employed.

A small (approximately 15 inch long) CO_2 laser has been assembled with an internal fluorescence cell for investigations of the control system. The laser is presently being tested.

Two ULE tubes with side holes for electrodes have been received from Corning and are presently being optically polished for tests as CO_2 laser tubes. Lifetime tests and thermal dissipation tests will be performed on these devices.

A large (70 cm, 9 mm bore) CO_2 laser tube, made available by QED Corporation, is being employed for investigating sealing techniques. This tube has been operated in a gas flowing system to give 12 watts power. The sealing techniques will be extended to the smaller tubes.

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Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 10

Period Covered: 15 September 1973 to 15 October 1973

23 October 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, the assembly of a small laboratory CO_2 laser has been completed, and approximately 1.5 watts output power has been obtained. The parts for the first sealed-off ULE quartz laser have been received. Work continues on an external modulator. A technical conference with Dr. Eric Hafner, contract monitor, reviewed the program.

2. Work Performed During the Month

A laboratory CO_2 laser has been constructed with an internal control cell. The overall length of the apparatus is approximately 22 inches with the laser on an order of 16 inches long. With two anodes and a single cathode in the center, the discharge sections are approximately 7 inches long. A flow system is employed with a gas mixture of 65% He, 20% N_2, 15% CO_2. On the order of 2 watts maximum power output is achieved. The control cell will employ the fluorescence signal at 4.3 μm to stabilize the laser. Investigations of the fluorescence and stabilization techniques are beginning with this apparatus.

An external control cell has been constructed for use with this laser. The cell is machined from invar and gold plated internally. A sapphire window on the side serves as a viewing port for the 4.3 μm radiation. A flat gold mirror is placed on the rear of the cell and a salt flat serves as the window on the other end. A single pass standing wave will be initially employed with this cell. The cell and entire test vacuum system has been helium leak detected, and is ready for experimentation.

Parts for the ULE quartz resonator have been received from Bond Optics. Copper electrodes are being prepared for the sealed-off laser. A CO_2-CO laser system will be investigated with the copper electrodes. During the discussion with Dr. Eric Hafner which was held on 16 October 1973, modification of the end plates to simplify the assembly was discussed. Dr. Hafner is having a flat ULE quartz plate (which will be gold plated) and a ½-meter Ge mirror constructed to use as alternates to the configuration which is currently available. The Ge mirrors are to be coated with reflective

(90%) and AR coatings by Laser Optics. In the apparatus employing the curved Ge mirror, a thin wall cylinder Pz element will be employed. Discussions with Roy Hanson of Gulton Industries indicate that they have no knowledge of the ability of their elements to serve as walls in a vacuum system. He referred us to Valpey-Fisher concerning the optical polishing of their elements and to Transducer Products concerning torsional Pz elements. The latter elements are being considered as part of a modulator system suggested by Dr. Hafner. A modulator employing a moving mirror mounted on a speaker and held aligned with telescopic tubing has been constructed by John Langley. The device in its initial tests has shown greater stability than previous configurations but has its optimum vibrations at a low frequency ($\sim$ 105 Hz). Approximately 3 mm displacement is achieved on very low input power.

Optical polishing of ULE quartz bodies and Pz elements has been completed by Q. E. D., but these pieces have not been received as yet. A laser belonging to Q. E. D. is being sealed off. With the laser valved off, an output of 4 watts has been achieved for periods of several days. Improved alignment of the tube with the mirrors will result in increased output.

A small 18" CO_2 laser has given an output of approximately 3 watts and will be available for heterodyning experiments.

3. Plans for the Next Month

During the next month, work will be performed in the following areas:

(1) Observation of the fluorescence at 4.3 µm with the internal control cell and stabilization of the CO_2 laser.

(2) Initial use of the external cell to compare results with the internal cell.

(3) Assembly of the ULE quartz lasers and filling for sealing-off.

(4) Continued investigations of the external modulator.

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MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 11

Period Covered: 15 October 1973 to 15 November 1973

26 November 1973

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, the ULE quartz lasers have been partially assembled. Observations have been made on the laboratory laser and internal fluorescence cell. Work continues on the various parts of the stabilized miniature source.

2. Work Performed During the Month

With two small ULE quartz laser tubes from Corning and the laser resonator parts from Bond Optics, small lasers are being assembled. Delays have been encountered in obtaining coated Ge mirrors and the necessary Pz elements. Copper electrodes have been made for the three lasers and tip-off tubes provided. The Ge mirrors have recently been received from Laser Optics. A 2" long 6mm bore tube and a 3" long 2mm bore tube have been assembled each with a flat total reflector and a flat 90% reflective Ge mirror. Both these resonators are presently mounted on the vacuum system for filling and sealing off. The copper electrodes will be employed with a CO_2, CO, He, Xe fill.

The larger ULE resonator, received from Bond Optics, has the electrode mounted in it. The flatness and parallelism of these components have been checked and found to be satisfactory. The curved Ge mirrors have been coated by Laser Optics and received this past week. Two small PZT cylinders for moving the curved mirrors from Transducer Products, and delivery is anticipated within about 2 weeks.

The small external modulator continues to have stability problems and consideration is being given to the torsional Pz technique discussed with Dr. Hafner during his last visit. Dr. Carol Thompson of Transducer Products has indicated that a split cylinder is employed for such a technique and that the size of the cylinder could be large if the displacement is large. The required displacements are currently being determined to provide Dr. Thompson the necessary information for calculating size and electrical characteristics.

Operation of the laboratory CO_2 laser has been performed during the past month in order to investigate the 4.3 μm fluorescence characteristics. The laser has operated over the pressure range from approximately 2 torr to 8 torr with power outputs from 100 mw to 2 watts. The laser can be detected with the 10.6 μm Hg Cd Te detector and locked satisfactorily to the doppler curve. The laser can be operated with the system valved off. Fluorescence has been detected at 4.3 μm by modulating the Pz element and observing the output on a lock-in amplifier. The fluorescence is weak. The Lamb dip has not been observed as yet, but improvements in the apparatus should result in its observation and locking of the system. Improvement in the 4.3 μm filter cooling is necessary. A study of the pressure effects in the control cell is necessary. Observation thus far have been limited to 100 millitorr pressure in the cell and approximately 200 milliwatts power output.

3. Plans for Next Month

During the next month, investigations will concentrate on the assembly of the small lasers, pending delivery of the Pz elements. The fluorescence observations will continue. The design of the complete control system will be made and reviewed in mid-December with Dr. Hafner at the quarterly conference.

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Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 12

Period Covered: 15 December 1973 to 14 January 1974

31 January 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, a technical meeting was held with Dr. Erick Hafner, Contract Monitor, to discuss progress of the program. A six-month interim technical report has been prepared and submitted for approval. Preparations are being made for the assembling of the over-all system while work continues on the small sealed-off laser and the laboratory fluorescence observations.

2. Work Performed During the Month

During the past month, work has been performed on the laboratory laser. Spectroscopic observations have shown that single line, single mode operation is achieved with a pair of apertures of 5 mm diameter within the laser cavity. An irregular line shape does occur and the reasons for this are being investigated. The Fresnel number for a 5 mm diameter aperture in this laser is approximately 1.1 so that the single pass diffraction loss for TEM_{10} is approximately 7% compared to approximately 0.6% for the fundamental TEM_{00} mode. Optimum operation occurs for power output on the order of 0.200 watts. This apparatus can now be used for the 4.3 µm fluorescence observations.

Investigations continue on the miniature CO_2 lasers. Piezoelectric elements have been received from Transducer Products and are currently being mounted on the existing small lasers. Several options exist for these small lasers and these are discussed in the Interim Report. An invar block has been optically polished by J. Noll Co. and will serve as the frame for a resonator for these small lasers. This block has been received from Noll and is currently being prepared for the laser. A Brewster's angle window will be used in this system so that the piezoelectric element will be external to the laser. The possibility of requiring a large voltage to tune to a line center necessitates the piezoelectric element to be external to the laser tube.

Discussions with Laser Optics indicate that the beam expander/collimator which precedes the control cell can be constructed with corrections taken for beam divergence. A diagram of the proposed system is being prepared to send to LO for determination of the necessary corrections.

Further work on the torsional modulator is awaiting calculations on size and voltage requirements from Dr. Carol Thompson of Transducer Products. The dimensions of this element will determine the final configuration which will be used for the system.

Dr. Charles Freed of Lincoln Laboratory called on January 24, 1974, to discuss the various aspects of the problem. He made several suggestions on the modulator, many of which have been considered and most of which consume high power. We indicated that we would plan a possible visit to Lincoln Lab in the near future for discussion of the entire apparatus.

During the discussion with Dr. Hafner at Fort Monmouth, the entire program was reviewed. It was tentatively planned to have the three systems practically assembled by April 1 with only the lasers and control cells with PbSe detectors needing continued work. Delivery of all components may delay this date.

3. Plans for the Next Month

During the next month, investigations on the laboratory laser and its application to saturation effects will continue. Improvements in the 4.3 μm detection are being pursued by including the cooled filter in the InSb detector. The parts are currently available for assembling the small lasers. The final ordering of parts and design of the overall system will be performed during this period. A schedule covering the final stages of the program is being established and will be included in the next monthly letter.

H-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 13

Period Covered: 15 January 1974 to 15 February 1974

4 March 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, investigations have continued on the small sealed-off laser, the laboratory fluorescence observations and the external modulator. Preparations are being made for the assembling of the three laser systems. Alternate beam scanners are being considered for the modulator system.

2. Work Performed During the Month

On the basis of information provided by Dr. Hafner, the use of a torsional piezoelectric element in the modulator system does not seem feasible at this time. As a result, alternate modulation schemes are being considered. The use of mechanical scanners has previously been investigated as a component in a frequency modulation system, but these have usually been dismissed as consuming too much power. A review of the literature indicates that two scanners are currently available which can meet our power requirements and also be compatible with the size requirements. One optical scanner, a taut band type, made by American Time Products (Bulova), has the disadvantage of being a mechanically resonant device and is probably susceptible to mechanical vibrations.

The other scanner is one of a series of devices made by General Scanning. The Model G-124 has characteristics which meet several of our requirements. This particular scanner has a sensitivity of 50 mA/degree, is relatively small and is sufficiently stable to be used in a modulator. The units are described as having wobble typically below 10 arc-seconds. The frequency range is from dc to approximately 980 Hz. The voltage required to produce a given drive current is

$$E = iR + L\frac{di}{dt} + B\dot{\theta}$$

where R = resistance of the coil (8 ohms), L = coil inductance (4 mH) and B = the back-emf constant (0.23 mV/degree/second). For approximately 1.5 degrees deflection, 0.729 volt is required with a power consumption of 0.055 watts. One of these units is available in the laboratory as part of an X-Y scanner, and tests will be performed to determine the use of these units.

The use of a stepped Ge plate moved perpendicular to the laser path is being considered as an alternate for a modulator. To go from an air path to a germanium path at a 200 Hz rate requires a Ge plate only 0.63×10^{-2} cm thick. A stepped Ge plate would require a step on the order of 1.5 mm to modulate on the order of 200 Hz.

During the past month, work continued on the small laser units. An invar block laser, described in the Interim Report, has been investigated. Breakdown problems and a small vacuum leak caused some delay in the operation of this unit. Uncertainty exists in whether laser action is occurring as an occasional pulsed output is observed in the initial firing of the discharge. Considerable heat is generated in the alumina tube, and this could be a disadvantage of the system. Currently, new heat sink electrodes are being put in the ULE quartz resonator, and piezoelectric elements capable of greater displacements are being mounted in some of the units. A beryllia tube is being employed with salt windows between external mirrors in order to determine if heating of the tube walls is a major factor in the inability of the small units to lase.

Fluorescence observations are being made with the internal control cell in the laboratory laser. An improved fluorescence signal is now observed. Instability due to the cooling of an external filter exists; a new InSb detector with built-in filter has been ordered. The Lamb dip has not been observed with this system as yet. Optimizing of the modulation and lock-in amplifier is being performed. Modulation at frequencies above 500 Hz does not result in an output signal on the lock-in while operation at frequencies on the order of 200 Hz does.

A quote has been obtained on the PbSe detector sets from Optoelectronics. The quote has been received for both 6 and 12 sets of detectors. Six sets would allow the use of 2 sets per control cell with the other two sides of the cell being mirror surfaces. A discussion with Dr. Yen of Optoelectronics indicates that the detectors can be employed in the vacuum without being affected by the CO_2 vapor, and that they do have a transmitting dielectric coating over them.

Parts are being constructed to hold the optical components for the small control system. One prototype unit will initially be assembled to serve as a model for the three units.

3. Plans for the Next Month

During the next month, investigations will continue on the small lasers, the fluorescence observations and the modulation scheme. Following a meeting with Dr. Hafner, Dr. Javan and Dr. Freed, all parts will be ordered for the final assembly of the units. Work will continue on the parts for a prototype unit.

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 14

Period Covered: 15 February 1974 to 14 March 1974

22 March 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, investigations have been continued on the small CO_2 laser, the fluorescence experiments and the components required for the assembly of a prototype stabilized system. Dr. E. Hafner and J. J. Gallagher visited C. Freed at Lincoln Laboratory and A. Javan at MIT on March 12 and March 13 to discuss aspects of the stabilization techniques. The discussions were extremely important to the work being performed on this contract.

2. Work Performed During the Month

During the past month, investigations have continued on the small CO_2 lasers. Previous observations have indicated the possibility of thermal effects being a cause for non-lasing of these small units. A small water-cooled unit has been fabricated to determine whether thermal effects have been causing the alumina and beryllia tubes not to lase. Piezoelectric elements with displacement capabilities on the order of 5 μm have been received from Jodon. These will provide greater tuning range for initially observing the transitions.

Returning from Boston on March 14, a visit with V. J. Corcoran at IDA provided an opportunity for discussion of our CO_2 laser problems. He indicated that he has operated a 5 inch water-cooled laser without the capability of length-tuning. Freed also indicated that some of his initial lasers had discharge lengths on the order of 4 inches. He did not state whether Pz elements were necessary but did state that they were water-cooled.

Fluorescence experiments have continued with the internal control cell. Fluorescence is observed although no Lamb dip has been observed. The salt window separating the laser from the control cell has cracked and has been replaced by a more flexible arrangement. While shut down to replace the window, the opportunity was taken to make some minor changes based upon our observations and discussions at Lincoln Laboratory and the MIT Physics Department. The effects of vibrations on deterioration of the fluorescence were pointed out by both Freed and Jim Small, and were evident

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MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 15

Period Covered: 15 March 1974 to 15 April 1974

1 May 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, work continued on the small CO_2 laser, fluorescence experiments and components for the stabilization system. The scanner for the modulator has been received and given its initial tests.

2. Work Performed During the Month

During the past month, investigations have been performed on several topics relevant to the stabilized molecular source. These subjects include the following:

(1) The most important item is the small CO_2 laser itself. Several versions of such a device have been considered. During the past month, a small water-cooled laser was operated with a gold rear reflector and a 95% germanium output reflector. The laser had one Brewster angle with the rear mirror attached directly to the tube. The tube was approximately 3 inches long and had a 3 millimeter bore. The water-cooling was employed since poor heat dissipation of the laser has been suspected. The 95% reflector, obtained from Laser Optics, was employed to obtain a higher Q than has been previously available. Despite these improvements, the 3 inch lasers have not shown any output as yet.

Discussions with Nelson McAvoy and John Degnan of NASA-Goddard have shed some light on small laser operation. While they have not operated a laser as short as 3 inches, they are working on small waveguide lasers. They suggested that a better rear reflector be used, since gold has a reflectivity on the order of 98%. Laser Optics has total reflectors of 99.4 ± 0.5%.

It was further suggested that small bore tubes in the 1-2 mm range be employed since the small bore tubes have higher gain. They did indicate that higher power dissipation results with the use of smaller bores. Tubes of both alumina and beryllia have been successfully used. From the tables of thermal conductivity, the advantage of BeO can be seen:

Material	T(°F)	Thermal Conductivity (BTU/HR·FT·°F)
Pyrex	100	0.68
Alumina	100	11.0
Aluminum	100	64
Beryllium Oxide	100	130

We have both alumina and beryllia tubing, but the bores for the BeO are small. One small BeO tube is being prepared for copper plating to provide a good heat sink and electrode contacts. It should be noted that, despite their good thermal properties, beryllia and alumina are poor resonator materials as their lengths vary drastically with temperature. An invar or ULE quartz resonator frame, as we plan on using, is necessary.

(2) Work has continued on fluorescence investigations at 4.3 µm. The internal control cell has been equipped with a variable disphram which allows single mode operation with approximately 200 mW output power. The mode structure is observed with an Optical Engineering 10.6 µm Display Plate. Fluorescence has been observed but it is not evident that the Lamb dip is present. An InSb detector with a filter built into the dewar is overdue for delivery from Judson. This arrangement is expected to be an improvement over the external cooling of the filter as in the present configuration. The Judson detector, originally scheduled for April 11 delivery, is now scheduled to be shipped on April 30.

(3) The General Scanning Model G-125 Optical Scanner has been received and tested for preformance. With a helium-neon laser, the power consumption for peak-to-peak deflection was checked for several frequencies. At 400 Hz, for a power consumption of 0.096 watts, a deflection of 4.1° was obtained while for 0.050 watts, the deflection was 2.3°.

(4) A prototype model of the stabilized system is being assembled to determine positioning of components. It is laid out so that the laser, collimator and control cell can be inserted as they become available. At the same time, a sketch of the system has been sent to E. Horvath of Custom Microwaves for suggestions on the component holders. The Optical Scanner has been mounted in this unit and presents the problem of making the stabilization system much larger than desired. A stepped mirror is being cut to serve initially as part of the modulator to determine size and shape of the optical beam. A drawing of the system has been sent to Jim Larin at Laser Optics to quote on the collimator, stepped mirror, beam splitter and laser mirrors. Quarter wave plates have been ordered from Cleveland Crystal. The detector arrays are to be delivered during May in two shipments. With the first delivery, the control cell will be assembled and the electronics for the detectors constructed.

(5) The metal-oxide-metal point contact detector has been received from Custom Microwaves, and two CO_2 lasers with gratings as rear reflectors are being set-up to heterodyne against one another with the MOM detector serving as a mixer. The HgCdTe detector will be used initially as a mixer to provide a comparison for the MOM unit.

3. Plans for the Next Month

Efforts will continue, during the next month, on the subjects discussed in Section 2 above. Particular emphasis must be placed upon the small laser and the observation of fluorescence while work is performed on the other aspects of the program.

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 16

Period Covered: 15 April 1974 to 15 May 1974

7 June 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. SUMMARY

During the past month, investigations have continued on the fluorescence and small laser activities. Dr. Hafner, contract monitor, visited the laboratory to review the program. Laser difficulties were encountered in the fluorescence apparatus, but this has been corrected. The overall laser control system has been re-designed in a linear configuration with internal modulation.

2. WORK PERFORMED DURING THE MONTH

During the past month, investigations have been performed on several topics relevant to the stabilized molecular source. These subjects include the following:

(1) Investigations of the small CO_2 laser itself. A small 3 inch discharge length laser was investigated. This device was operated water cooled to remove the question of heat dissipation. No laser action has thus far been observed. A 95% output mirror has been employed with a Max-R rear reflector from Laser Optics. Salt windows were employed. Calculations indicate that this system should oscillate. The salt windows do not appear to be of top quality, however. Germanuim windows with 98% reflectivity have been received, and these will be employed to increase the resonator Q. For the final version of the laser, ZnS windows have been received. The small lasers will have an invar block frame, beryllium oxide tube (initially with 1.5mm bore), the ZnS windows and 98% reflective mirrors at each end. One mirror will be mounted on a PZ element for laser stabilization and modulation. The output from one mirror will be the useful signal output while the output from the second mirror will serve as the signal for controlling the laser.

A telephone conversation with Dr. Hans Heiselmeier and Mr. Charles Bickart allowed us to review the small laser system and receive their comments. Opinions seem to point toward the major difficulties lying in possible window losses, a need for higher resonator Q or poor alignment.

(2) During Dr. Hefner's visit, we looked at the fluorescence system using an external cell with a new InSb detector. The laser operated poorly throughout the observations. Fluorescence was observed but the Lamb dip was not observable. The signal strength was low, being on the order of 250 nanovolts. The noise level of the new detector with a filter is much lower

than the previously employed detector.

Since those observations, the rear mirror has been replaced and a new gas supply is available. Considerable increase in power output is obtained. Single mode operation is easily achieved with the aperture. However, single line operation is only achieved with considerable tuning and further aperture reduction, resulting in power loss. Observations with the Jarrell-Ash spectrometer indicate that the P(20), P(18) and P(16) transitions are competing. Observations on the fluorescence output indicate that the power level is approximately the same as previously observed. Recordings have been made of the fluorescence derivative and the output obtained by chopping the beam. The latter traces show the output rides on a 4.3μm background which comes directly from the laser. This has also been observed by putting the laser signal directly into the InSb detector. No laser signal is observed in this manner because of the narrow band characteristics of the detector and filter. The loss of the derivative or chopped signal is further observed by replacing the CO_2 in the external cell with air. The 4.3μm background signal is not observed in the derivative display when modulation is used on the PZ element. Improved power output and a better alignment of the control cell are now being considered. Aperturing and defocusing of the laser output minimizes the 4.3μm background.

(3) The assembly of a system employing internal modulation rather than external modulation is progressing. The optical scanning system for external modulation was employed with a stepped mirror. Considerable work is needed to obtain the correct shape of the mirror to achieve a good superposition of the two signals.

The 3 CdS quarter wave plates have been received from Cleveland Crystal and a mount is being prepared for them. The sets of detector arrays have been received from Optoelectronics, and housings are being assembled for them. Because of the large areas of these devices, a large bias voltage (~500V) is required. The thermoelectrically cooled PbSe detector has been mounted with a 4.3μm filter to compare with the InSb device.

3. WORK PLANNED DURING THE NEXT MONTH

During the next month, investigations will continue on the small laser and fluorescence studies while the assembly of the 3 controlled units will be carried out.

File: A-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 17
Period Covered: 15 May 1974 to 15 June 1974

30 June 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. SUMMARY

During the past month, investigations have continued on the fluorescence and small laser activities. The Lamb dip has been observed in a cell within the laser cavity. Experiments are continuing on the characteristics of this dip and on moving the cell outside. The construction of parts for the laser control system has continued.

2. WORK PERFORMED DURING THE MONTH

During the past month, investigations have been performed on several topics relevant to the stabilized molecular source. These subjects include the following:

(1) Fluorescence observations have continued with the laboratory laser and both external and internal control cells. Observations have been made on the external control cell, optically aligned to provide a standing wave with the laser signal. The cell has been operated at approximately 100 millitorr. For single line operation from the CO_2 laser, the power output has been low, usually below 100 milliwatts. Some 4.3 μm background from the laser has been observed but this can now be minimized. With the external cell, the signal has continued to be small. A peak-to-peak of the flourescence derivative is less than 500 nanovolts input to the phase sensitive amplifier. As a result, the noise level is not far below the signal level. A stronger signal is obtained with the chopper system. Actually signals showing an indication of a Lamb dip have been obtained with the AM system, but these have always been too weak to be assured that the dip is occurring.

With the internal cell, the Lamb dip has been observed with considerable strength. The observations made thus far have been for pressures of 100 millitorr and 75 millitorr with the latter providing the better signals.

The signals obtained with the internal cell are shown with the accompanying figures. Figure 1(a) shows the derivative of the Lamb dip for a CO_2 pressure of 75 millitorr. This trace, was taken on the 10 μV sensitivity range of the PAR lock-in for a 300 millisecond time constant. With the sensitivity increased to the 2 μV scale and a time constant of 1 second, Figure 1(b) is obtained. The peak-to-peak voltage on the PZ corresponds to

15 volts. We have checked the voltage sensitivity of the piezoelectric elements since these initial observations by determining the half wavelength displacement with the Jarrell Ash spectrometer. The voltage sensitivity is approximately 0.347 μm/100 V so that the frequency width of the derivative peaks is about 2.61 MHz. This is a broader line than that observed by Freed. As Freed has indicated below 100 millitorr, the linewidth is mainly determined by power broadening and by the molecular transit time across the diameter of the incident beam. Power broadening can be occurring in the observations which we have thus far made.

The aperture in the laser was opened to determine the limit to which we could increase the aperture and still maintain the Lamb dip. Figures 2 and 3 show the effects. The power increase was on the order of a factor of 3. In Figure 3(b), the line width increased by a factor of 1.5 so that, if the measured PZ sensitivity is correct, the width of the Lamb dip derivative was on the order of 4 MHz. The peak-to-peak amplitude of the derivative was 3.3 μV.

For these observations, the reflectivity of the output mirror was 95%, the modulation was 30 volts at 520 Hz, the lock-in time constant was either 1 second or 300 milliseconds. The recorder curves were taken by hand tuning the auxiliary power supply for the PZ drive. A motor drive has been made up to provide a slow tuning arrangement for the power supply.

Currently, investigations are being made a) to lower the power as far as possible to determine the minimum power required to observe the Lamb dip and to determine the effects of power saturation; b) to determine the Lamb dip characteristics as a function of the modulation frequency and voltage amplitude. The laser will be locked to this internal Lamb dip. The major objective is to go to the external cell, but the information obtained from the internal cell is important for external use. The thermoelectric PbSe detector will be used for internal observations to compare the relative sensitivities.

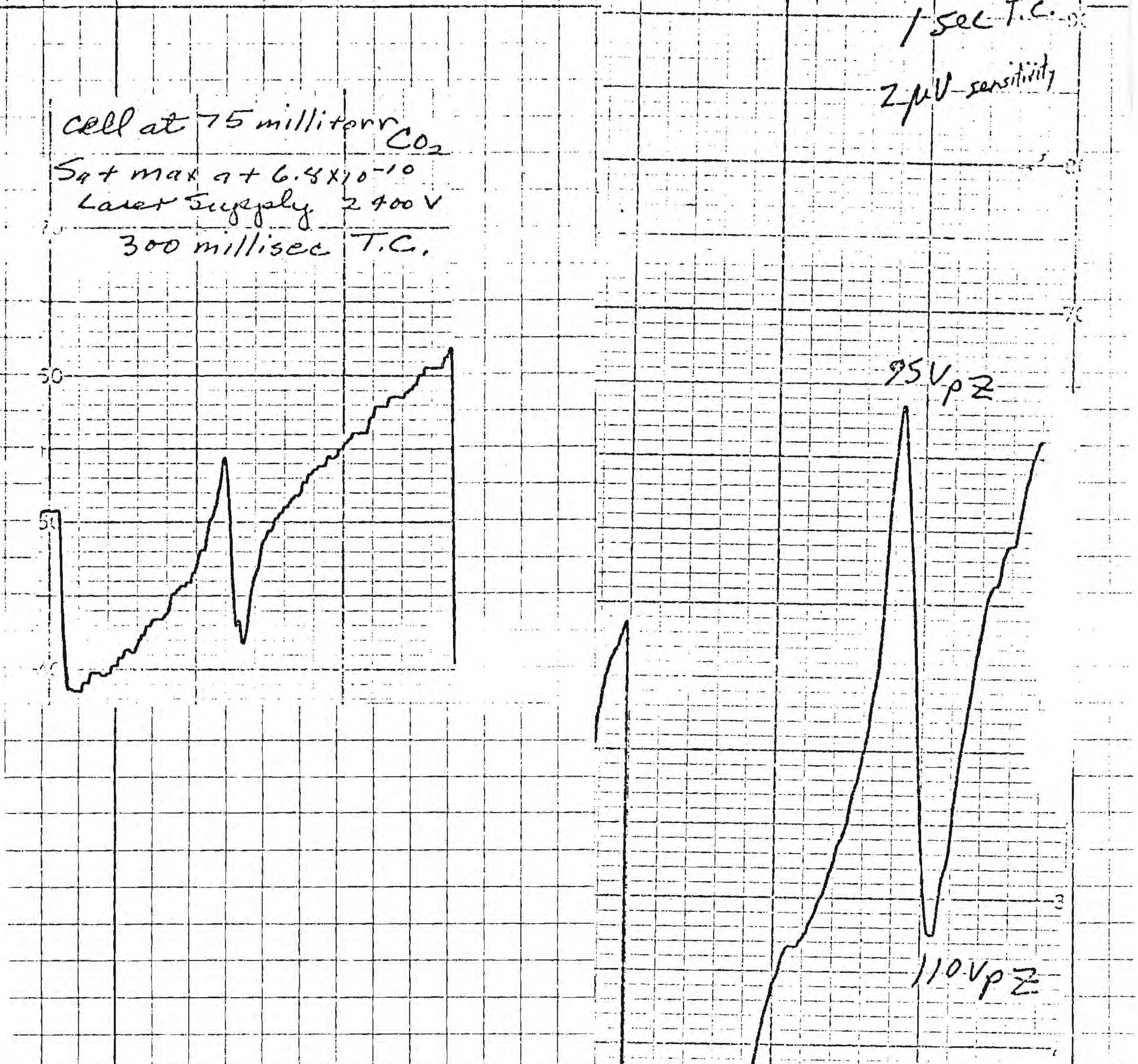
(2) Investigations have continued on the small laser tubes while assembly of the invar block lasers has been progressing. A six-inch water-cooled laser is operating. Zinc selenide windows have been obtained for the final assemblies. BeO tubes with 1.5 mm bores are being shipped by Consolidated Ceramics for the invar block lasers.

(3) The parts for the small laser control system are being constructed. All three quarter wave plates have been assembled in mounts for the system. Poor responses from vendors have delayed the ordering of optics for the beam expander/collimators, but the necessary lenses are now on order. The lenses for a Galilean telescope arrangement are a -1/2-inch focal length, 1/2-inch diameter diverging lens, and a 3-inch focal length, 1-inch diameter collimating lens. These will be mounted in cylinders to yield a magnification of 6. The cells have been designed for the room temperature PbSe detectors, and we are currently waiting for square (1-1/4" x 1-1/4" O.D.) tubing which will house the elements. Copies of the detector data sheets are enclosed. The high detector bias (500 V) presents an undesirable aspect for the use of large area room temperature detectors.

3. WORK PLANNED DURING THE NEXT MONTH

During the next month, investigations will continue on the internal control cell and be extended to the use of the external control cell. The investigations of the small lasers will continue while assembly of the three complete units will be performed.

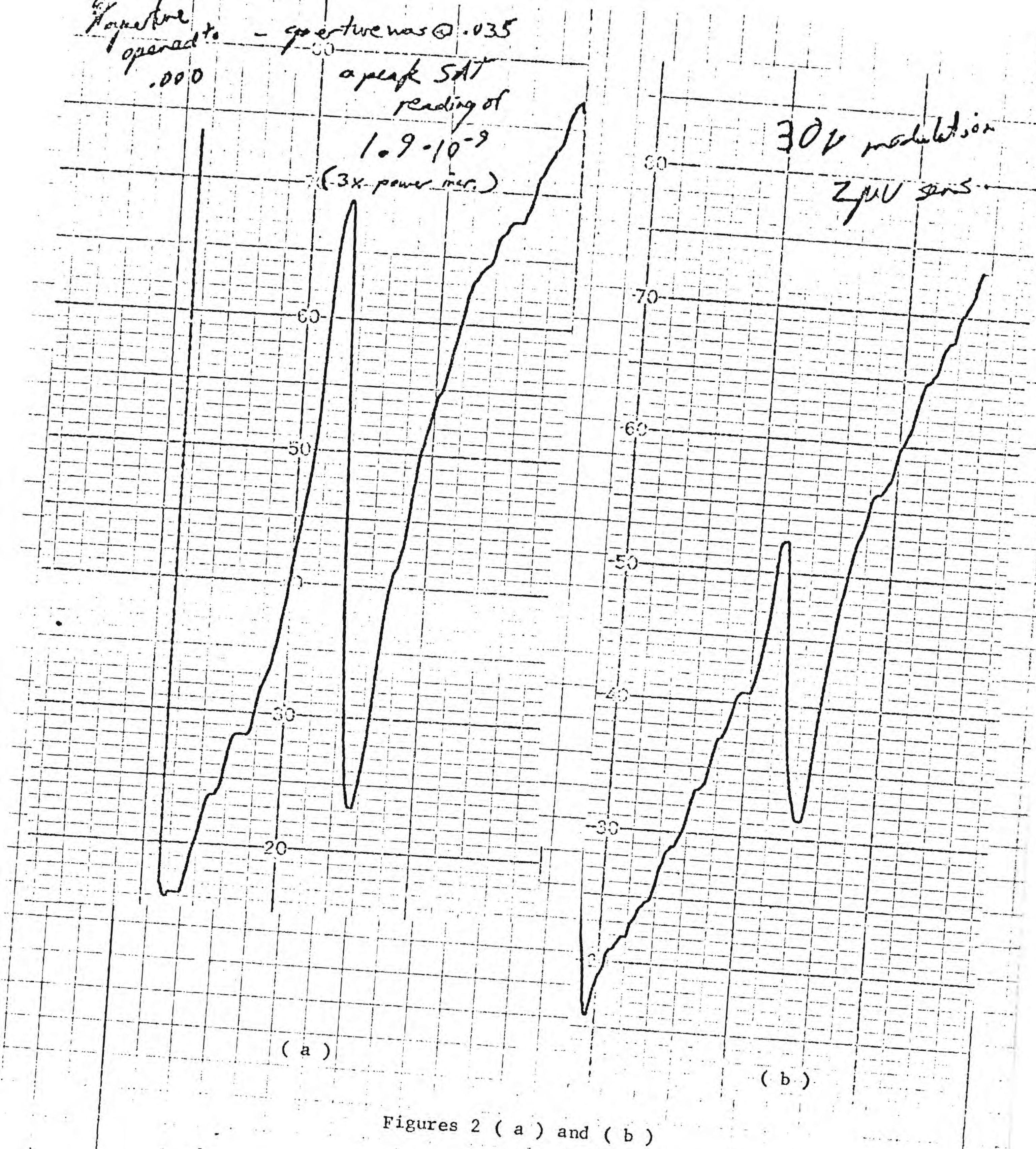
Cell Pressure Reduced



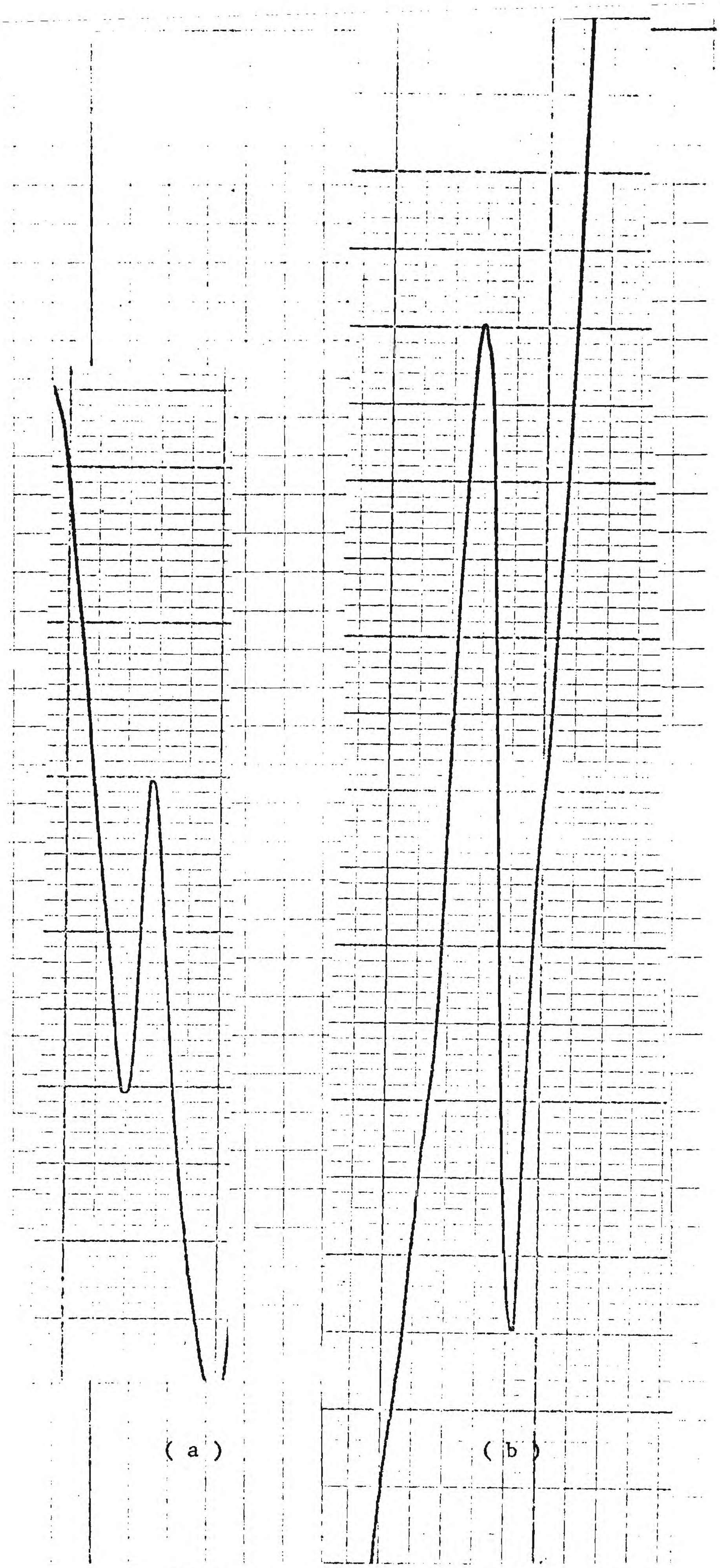
Increased sensitivity and T.C. (to 1 sec.)
Peak-to-peak on PZ ≅ 15 v
Check sensitivity of PZ elements. 15 volts → 3.10 MHz

(a)   (b)

Figures 1 (a) and 1 (b)



Figures 2 (a) and (b)



(a) (b)

Figures 3 (a) and 3 (b)

OPTOELECTRONICS, INC.
1309 Dynamic Street - Petaluma, Ca. 94952

DATA SHEET

PROJECT NO. PPI- 1852

DATE May 20, 1974

DETECTOR MATERIAL PbSe

PART NUMBER OE-10 X

Q.A. ACCEPT QC-1 5 [illegible]

TESTED BY E.P.

PG. 1 OF 2

ELEMENT SERIAL NUMBER	THERMOELECTRIC COOLER @		THERMISTOR RESISTANCE		DETECTOR DARK RESISTANCE		DETECTOR BIAS (VOLTS)	SIGNAL (µVOLTS)	NOISE (µVOLTS)	SIGNAL TO NOISE RATIO	RESPONSIVITY (λpk, 1000) (VOLTS/WATT)	D* (λpk, 1000, 1) (CM Hz 1/2 W⁻¹)
	VOLTS	AMPS	AMBIENT (KΩ)	COLD (KΩ)	AMBIENT (MΩ)	COLD (MΩ)						
1					.081		500	195	0.55	355	84.5	1.35×10^9
2					.094		500	195	0.45	433	84.5	1.65×10^9
3					.060		500	180	0.35	514	78.0	1.96×10^9
4					.103		500	225	1.00	225	97.5	0.86×10^9
6					.150		500	340	0.85	400	147	1.52×10^9
7					.146		500	370	1.30	285	160	1.09×10^9
8					.055		500	120	0.35	343	52.0	1.31×10^9
10					.121		500	330	0.45	733	143	2.79×10^9
11					.086		500	265	0.75	353	115	1.35×10^9
19					.057		500	125	0.25	500	54.2	1.91×10^9

TEST CONDITIONS

BLACKBODY TEMPERATURE 500 Degrees Kelvin

FLUX DENSITY 2.98×10^{-6} Watts/CM²

CHOPPING FREQUENCY 1000 Hertz

NOISE BANDPASS 10 Hertz

OPERATING TEMPERATURE 298 Degrees Kelvin

HEAT SINK TEMPERATURE N/A Degrees Kelvin

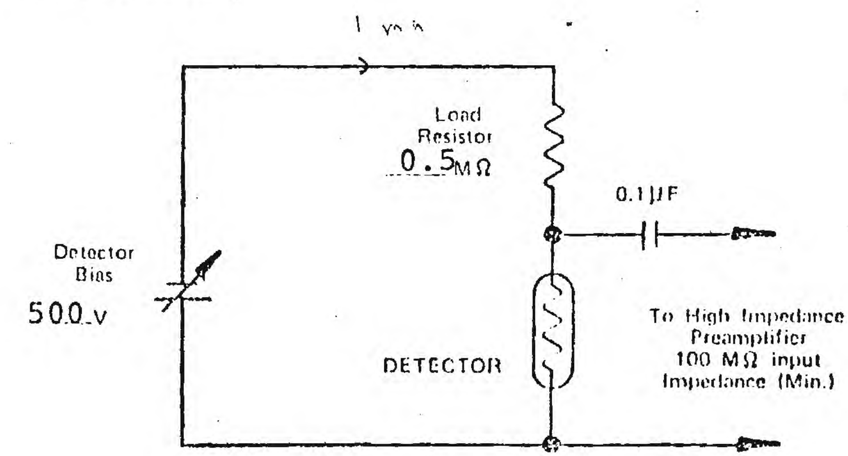
DETECTOR ELEMENT SIZE 1.27 X 6.1 CM

AREA 7.74 CM²

$\frac{D^* (\lambda pk)}{D^* (BB)}$ = 10

APPROVAL [illegible]

TEST SCHEMATIC



OPTOELECTRONICS, INC.
1309 Dynamic Street - Petaluma, Ca. 94952

DATA SHEET

PROJECT NO. PPI- 1852

DATE May, 20, 1974

DETECTOR MATERIAL PbSe

PART NUMBER OE-10X

Q.A. ACCEPT QC-1 5-21-

TESTED BY E.P.

PG. 2 OF 2

ELEMENT SERIAL NUMBER	THERMOELECTRIC COOLER @		THERMISTOR RESISTANCE		DETECTOR DARK RESISTANCE		DETECTOR BIAS (VOLTS)	SIGNAL (μVOLTS)	NOISE (μVOLTS)	SIGNAL TO NOISE RATIO	RESPONSIVITY (λpk, 1000) (VOLTS/WATT)	D* (λpk, 1000) (CM Hz $^{1/2}$ W $^{-1}$)
	VOLTS	AMPS	AMBIENT (KΩ)	COLD (KΩ)	AMBIENT (MΩ)	COLD (MΩ)						
13					.063		500	170	0.25	680	73.7	2.60×10^9
15					.079		500	180	0.40	450	78.0	1.72×10^9

Electrical Measurement of 5 Element Array was made with elements in parallel.

OPTO E 003

File: A-1477

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 18
Period Covered: 15 June 1974 to 15 July 1974

5 August 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the past month, the major effort has been toward the construction of the laser control system. Observations continued on the small lasers and the Lamb dip linewidths comparable with those obtained by Freed have been obtained at low power levels.

2. Work Performed During the Month

During the past month, work continued toward the construction and assembly of three final models of the stabilized CO_2 laser, although the small tubes do not work as yet. It is hoped that they will work in the final version currently being assembled. The components being constructed include the laser, collimator/expander and detector control cell. The control cell houses four of the detector arrays and will be filled with CO_2 to approximately 50 millitorr. These will be tested with the laboratory laser for comparison with the existing cells.

Investigations continue on the fluorescence observations. The internal cell was employed with the laser power output reduced to approximately 3 milliwatts which corresponds to approximately 50 milliwatts inside the laser resonator. The linewidth (total half-power) was reduced to 0.8 MHz for a pressure on the order of 100 millitorr. This figure is compatible with Freed's measurements. No further changes in linewidth was evident as the power was reduced. The fluorescence observations are currently being performed with an external cell.

3. Work Planned During the Next Month

During the next month, final assembly of the three systems will be performed. The control cells will be tested, the fluorescence work will be concluded and a final report will be prepared on the investigations performed during this time.

MINIATURE MOLECULAR FREQUENCY STANDARD

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Contract No. DAAB07-73-C-0065

Monthly Progress Report No. 19
Period Covered: 15 June 1974 to 15 August 1974

22 October 1974

Project Director: J. J. Gallagher
Contract Monitor: E. Hafner

Prepared for

USA Electronics Technology and Devices Laboratory
Semiconductor and Frequency Control Devices Technical Area
Fort Monmouth, New Jersey 07703

1. Summary

During the final period of the contract, assembly of the deliverable items has been underway. Tests have been performed on the room temperature PbSe detection schemes. Laser action has been obtained from a water-cooled CO_2 laser with a length of 6 inches. In addition, operation of room temperature lasers (approximately 6 inches and 4 inches in length) has been achieved.

2. Work Performed During the Month

The room temperature PbSe detectors have been employed with an external control cell. The detectors are mounted internally on the side-walls of the control cell. The signals from the four detectors in each cell are added before being applied to the lock-in amplifier. A salt window serves as the entrance window while a mirror is mounted on the rear plate. It has been possible to detect the 4.3 μm fluorescence with these control cells, but thus far no Lamb dip has been observed. The observations have been performed with control cell pressures on the order of 50-150 millitorr. The laser power level has been approximately 100-200 mW, which should be adequate for saturation of the resonance. The signal level of the fluorescence is 1-2 orders of magnitude less than the fluorescence signal strength observed with the cooled InSb detector. The alignment for the standing wave in the control cell is critical; on several occasions, the possibility of the presence of a Lamb dip was considered; however, the suspicious dip was not significantly distinguished from noise. In order to enhance the signal, a Fabri-Tek signal averager was employed, but again no distinguishing features were evident.

The small water-cooled laser, six inches in length, is capable of approximately 1.5 watts output for 15-20 watts input. It has lased at 250 mW for input power of the order of 3 watts. Smaller input power does not result in an observable laser output. The laser operates with a Max-R total back mirror and a 98% output mirror with no internal windows. Many of the difficulties observed with the small lasers with internal windows can be attributed to the losses in the windows. The water-cooled laser can be sealed off, and lasing action is maintained.

A small laser, six inches long including the piezoelectric tuner, has been constructed from alumina. An output of approximately 250 mW has been obtained. In addition, one of the small invar blocks with an alumina tube has been operated as a laser with a power output of approximately 100 mW. The tube ID used for each of these units is approximately 4 mm. A comparison with a small waveguide laser should be made. Thus far, it has not been possible to operate these room temperature lasers in a sealed-off mode, quite probably due to the heat dissipation problems. The substitution of BeO tubes for the alumina is expected to correct this situation.

The assembly of the deliverable units will be completed shortly. The units will consist of a water-cooled CO_2 laser, beam-splitter, quarter wave plate, beam expander-collimator and the PbSe control cell. While the control cell has yet to show a Lamb dip, the goal which was originally set at the start of the contract appears feasible and should be achieved with continued effort.

Upon final assembly of the three laser units, delivery will be completed. The final report is in preparation and should be completed by October 31, 1974.

Preliminary CO_2 Laser	Months After Start 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1. Order Invar Rods	Received
2. Order Irtran Windows	△ (1-27-73)
3. Order Quartz Tubing	Available from glassblower
4. Order Mirrors	△ (1-25-73)
5. Order Electrodes	constructed by glassblower or purchased from Coherent Radiation
6. Order Piezoelectric Elements	▲
7. Construct Laser Test Bed	△ (1-22-73)
8. Assemble Vacuum System for Flow System	On schedule
9. 4.3 μm Detector	▲ PbSe detectors received △ InSb detector ordered; Amplifiers to be constructed
10. Control Cell	Internal cell under construction
11. Improvement of Existing Power Supply	On schedule
12. Glass Blower Assembly	On schedule

△ - scheduled Delivery

▲ - Received

Electronics	Months After Start 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1. Power Supply Check out	Under consideration
2. 4.3 μm Detector Pre-amp	To be constructed
3. Lock-in and Reference for Modulator	Purchasing Lansing Stabilizer for Initial Tests
4. Electronics for Modulator	Included in Lansing Unit
5. Amplifier and Servo Components for Piezoelectric Tuner	Included in Lansing Unit
6. Servo-control system analysis	To begin this month (Jan/Feb)

4.3 μm Detector

1. Detector for Initial Experiments:

   a. PC vs Pyroelectric

   b. Cooled or ambient

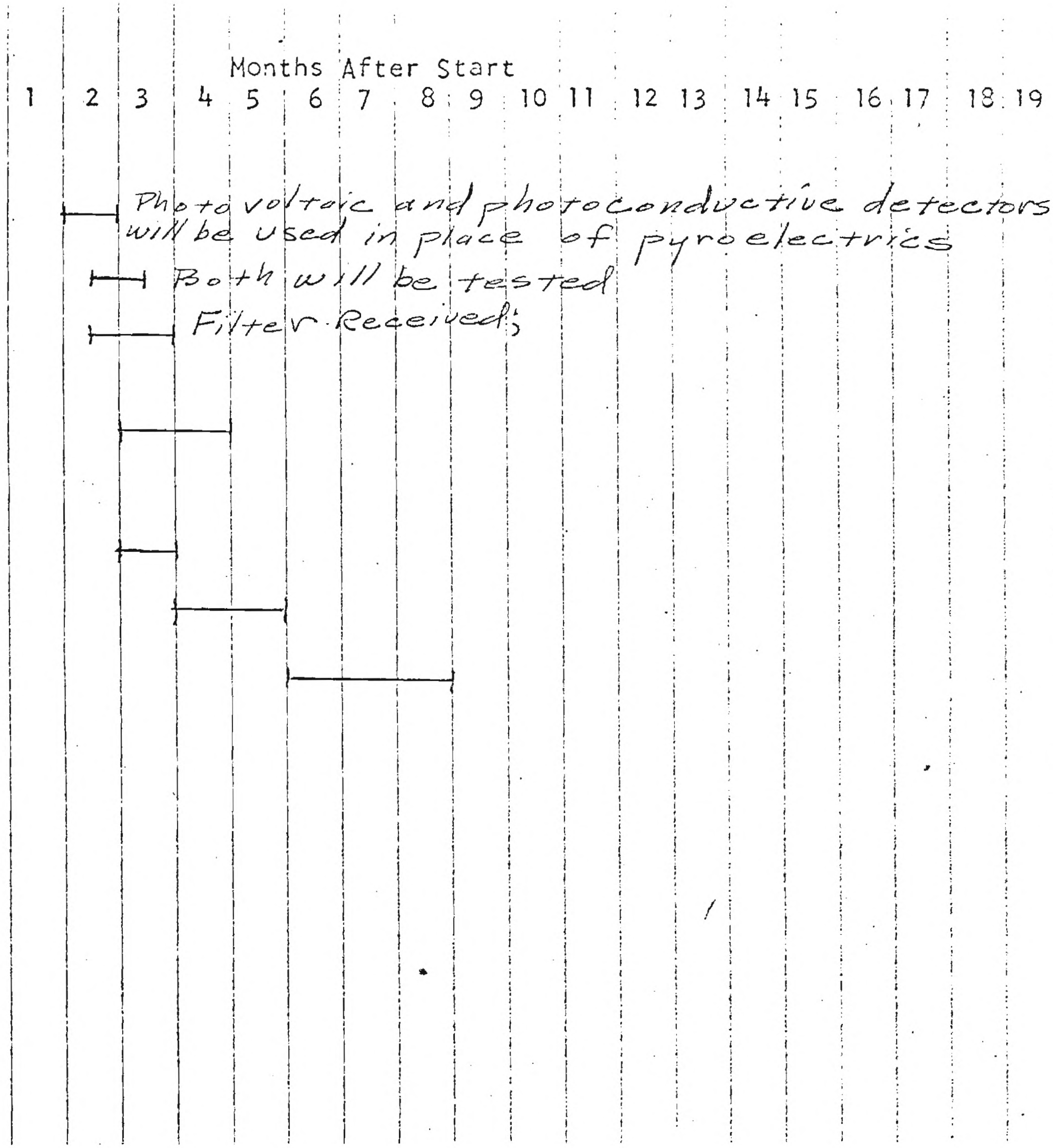
   c. Collection Optics and Filtering

2. Reqiured Characteristics: Detectivity, Bandwidth and Risetime

3. Initial pre-amp design

4. Consider ambient Pb Se

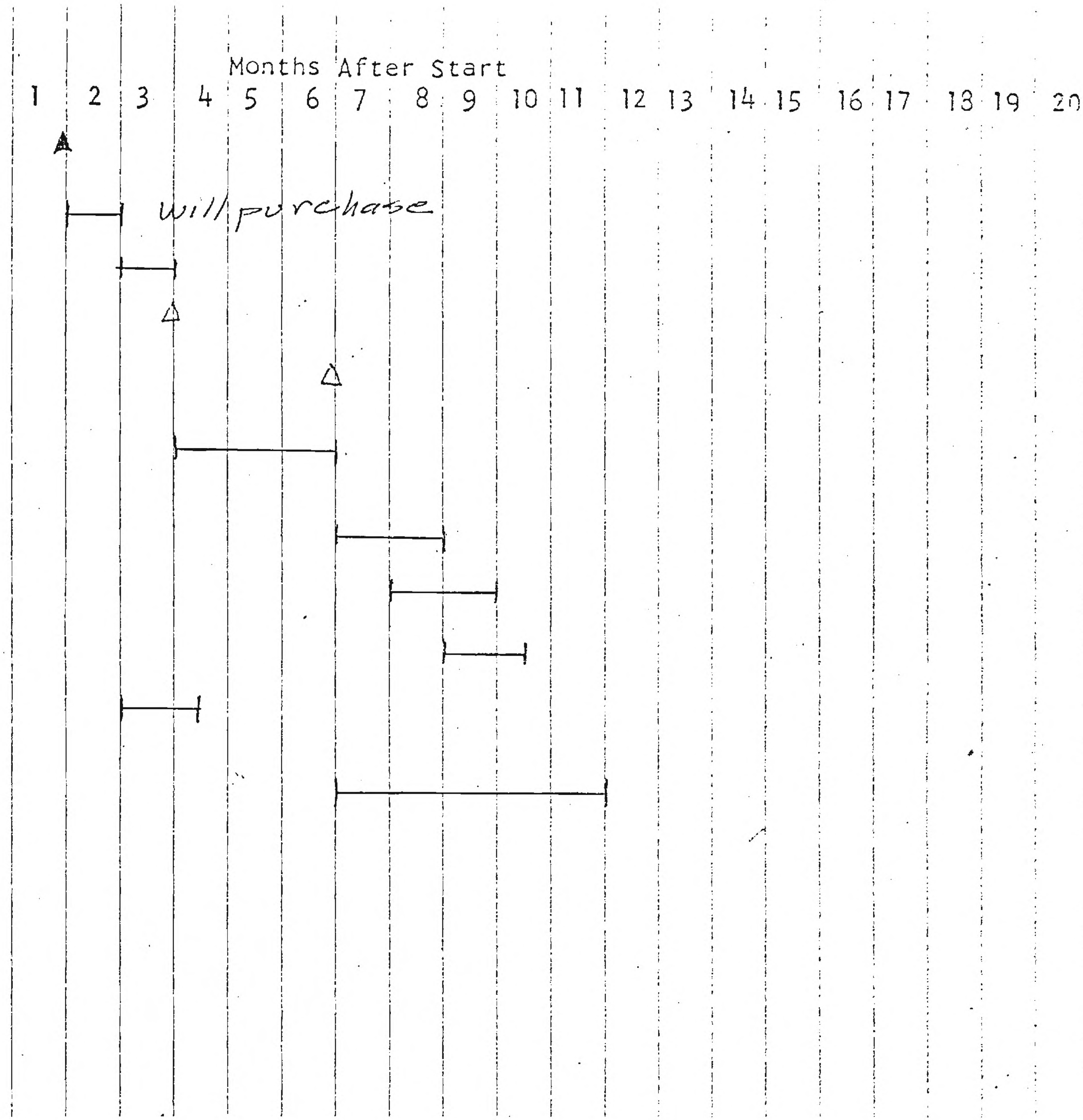
5. Pb Se film on the side of control cell

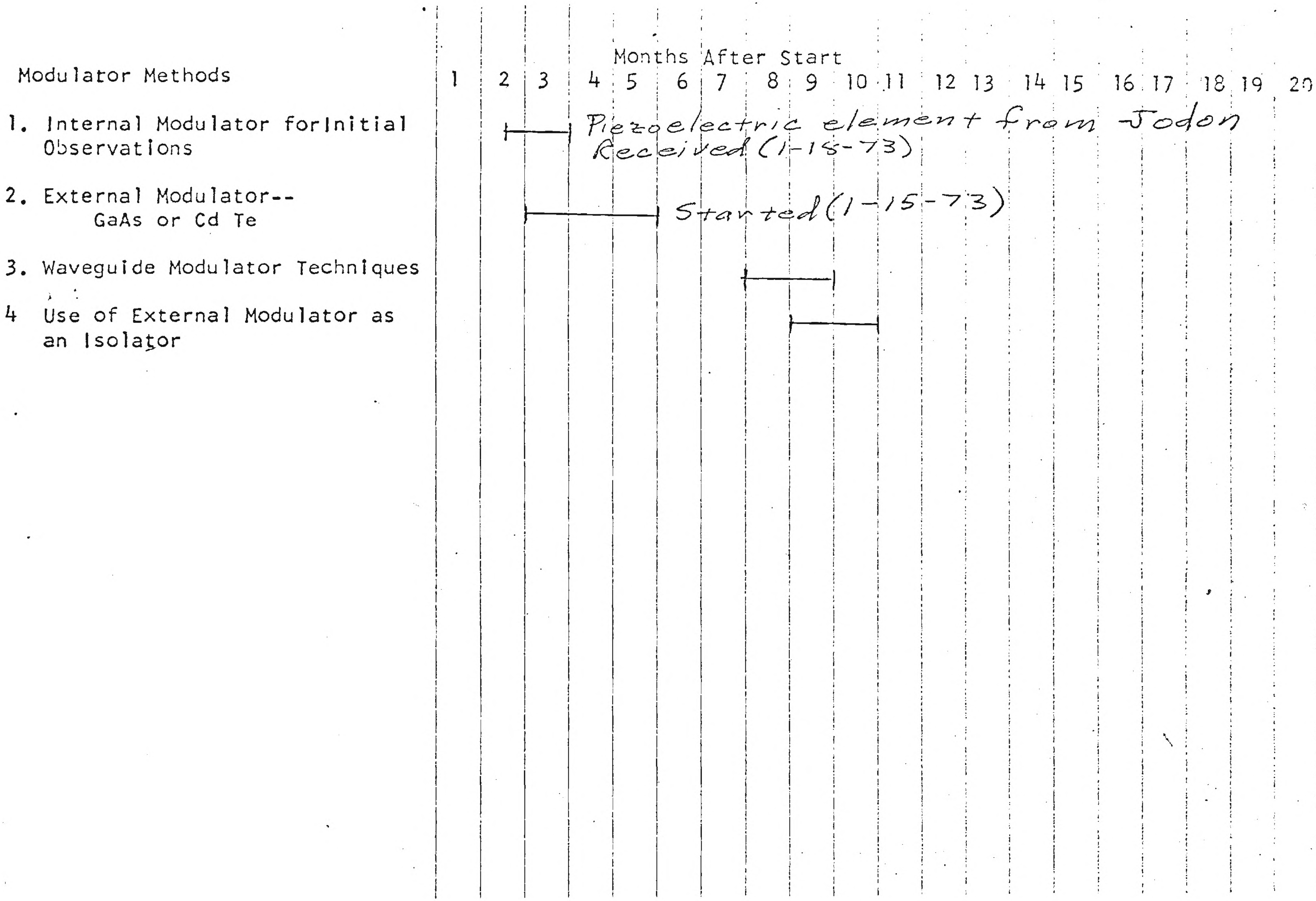


Metal-Metal Oxide Diode

1. Price from E. Horvath
2. Purchase or design/construct?
3. Provide required configuration
4. If purchase, order
5. Delivery
6. If design and construct
7. Initial observations--
   a. detedtion

   b. mixing
8. Biasing effects
9. Whisker and metal materials;
   wire sizes
10. Compare with other detectors
   for heterodyning--
   pyroelectric;
   photovoltaic




Modulator Methods
Months After Start
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
1. Internal Modulator for Initial Observations
Piezoelectric element from Jodon Received (1-15-73)
2. External Modulator-- GaAs or Cd Te
Started (1-15-73)
3. Waveguide Modulator Techniques
4 Use of External Modulator as an Isolator

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
15 January 1973

The following charges have been incurred against the contract during the period 15 November 1972 through 31 December 1972:

Personal Services	$1,895.36
Materials and Supplies	$ 69.58
Travel	$ 352.42
Overhead and Retirement	$1,175.68
TOTAL	$3,493.04

The breakdown of personal services is the following:

James J. Gallagher	$1,551.05
Robert G. Shackelford	$ 171.20
Machinists, Technicians	$ 173.11
TOTAL	$1,895.36

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
13 February 1973

The following charges have been incurred against the contract during the period 1 January 1973 through 1 February 1973:

Personal Services		$1,286.90
Materials and Supplies		$6,996.50
Overhead and Retirement		$ 785.09
	TOTAL	$9,068.49

The breakdown of personal services is the following:

James J. Gallagher		$ 655.37
R. G. Shackelford		$ 171.20
Technicians		$ 228.95
Machinists		$ 231.38
	TOTAL	$1,286.90

The breakdown of materials and supplies is the following:

Eltek Corp. (HgCdTe detector)		$3,375.00
Lansing 80-214 Laser Stabilizer		$1,590.00
Optoelectronics InSb Detector		$ 850.00
Optoelectronics PbSe Detectors (2)		$ 350.00
Valpey CO_2 Laser Mirror		$ 165.00
Jodon Piezoelectric Controller		$ 126.50
Eastman Kodak Irtran Windows (3)		$ 226.50
Matheson Gases		$ 21.60
Dwyer Gas Flow Instruments		$ 44.80
Coherent Radiation Electrodes		$ 49.68
Adolf Meller Sapphire Windows		$ 31.20
OCLI Narrow Band Filter		$ 125.00
Miscellaneous Supplies		$ 41.72
	TOTAL	$6,996.50

The utilization and characteristics of these materials will be described in the next monthly letter.

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COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
15 March 1973

The following charges have been incurred against the contract during the period 1 February 1973 through 1 March 1973:

Personal Services		$1,895.45
Materials and Supplies		249.49
Travel		254.42
Overhead and Retirement		1,180.14
	TOTAL	$3,579.50

The breakdown of personal services is the following:

J. J. Gallagher		$ 655.37
A. McSweeney		358.45
Machinists, Technicians, etc.		881.63
	TOTAL	$1,895.45

The breakdown of materials and supplies is the following:

Electronic Parts		$ 172.68
Metals		15.96
Miscellaneous Supplies		60.85
	TOTAL	$ 249.49

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
11 April 1973

The following charges have been incurred against the contract during the period 1 March 1973 through 31 March 1973:

Personal Services		$2783.38
Materials and Supplies		187.87
Overhead/Retirement		1733.43
	TOTAL	$4704.68

The breakdown of personal services is the following:

J. J. Gallagher		$ 786.45
A. McSweeney		83.64
J. B. Langley		597.06
Technicians/Machinists		1316.23
	TOTAL	$2783.38

The breakdown of materials and supplies is the following:

Miscellaneous Supplies	$187.87

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
8 May 1973

The following charges have been incurred against the contract during the period 15 November 1972 through 31 December 1972:

Personal Services		$1,958.85
Materials and Supplies		$ 133.10
Overhead and Retirement		$1,317.80
	TOTAL	$3,409.75

The breakdown of personal services is the following:

James J. Gallagher		$ 655.37
Robert G. Shackelford		$ 171.20
J. B. Langley		$ 165.85
Machinists, Technicians		$ 966.43
	TOTAL	$1,958.85

The Materials and Supplies charges were all for small laboratory supplies.

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
26 June 1973

The following charges have been incurred against the contract during the period 1 May 1973 through 31 May 1973.

Personal Services	$ 845.15
Materials and Supplies	427.77
Overhead and Retirement	617.24
TOTAL	$1890.16

The breakdown of personal charges is the following:

R. G. Shackelford	$ 171.20
A. McSweeney	227.02
Technicians and Machinists	446.93
TOTAL	$ 845.15

The breakdown of materials and supply charges is the following:

Xerox Charges	$ 10.20
Photo Lab Report Charges	16.50
Engelhard Minerals - Gold Paint	50.00
Glass lab charges, small optical parts, miscellaneous lab parts	351.07
TOTAL	$ 427.77

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
12 July 1973

The following charges have been incurred against the contract during the period 1 June 1973 through June 20, 1973:

Personal Services		$1917.65
Materials and Supplies		153.74
Overhead and Retirement		1148.97
	TOTAL	$3220.36

The breakdown of personal services is the following:

James J. Gallagher		$ 480.61
R. G. Shackelford		205.44
A. McSweeney		131.43
Technicians, Machinists, Draftsmen		925.07
Student Assistants		175.10
	TOTAL	$1917.65

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
21 August 1973

The following charges have been incurred against the contract during the period 1 July 1973 through 31 July 1973.

Personal Services		$3366.58
Materials and Supplies		1394.15
Travel		216.20
Overhead and Retirement		2054.00
	TOTAL	$7030.93

The breakdown of personal charges is the following:

J. J. Gallagher		$1558.27
R. G. Shackelford		190.82
A. McSweeney		577.62
Student Assistants		251.00
Technicians and Machinists		788.87
	TOTAL	$3366.58

The breakdown of materials and supply charges is the following:

Bond Optics		$ 650.00
Xerox Charges		24.42
Corning Glass		188.20
Harshaw Chemical		108.54
Glass lab charges, small optical parts, miscellaneous lab parts, electrode materials		422.99
	TOTAL	$1394.15

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
20 September 1973

The following charges have been incurred against the contract during the period 1 August 1973 through 31 August 1973.

Personal Services		$2,198.83
Materials and Supplies		645.42
Overhead and Retirement		1,518.15
	TOTAL	$4,362.40

The breakdown of personal charges is the following:

J. J. Gallagher		$ 320.82
A. McSweeney		464.91
R. D. Wetherington		341.24
R. G. Shackelford		190.82
Machinists		205.66
Technicians, Student Assistants		543.17
Secretarial, Administrative Personnel		132.21
	TOTAL	$2,198.83

The breakdown of materials and supply charges is the following:

Bond Optics		$ 355.00
Matheson Gas Products		152.70
Liquid Nitrogen		26.00
Consolidated Ceramics		50.00
Miscellaneous Lab Parts		61.72
	TOTAL	$ 645.42

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
22 October 1973

The following charges have been incurred against the contract during the period 1 September 1973 through 30 September 1973.

Personal Services		$2340.64
Materials and Supplies		224.76
Overhead and Retirement		1506.58
	TOTAL	$4071.98

The breakdown of personal service charges is the following:

J. J. Gallagher		$1306.20
A. McSweeney		338.12
Technician, Machinists		377.34
Student Assistants		74.60
Administrative Assistance		244.38
	TOTAL	$2340.64

and supply charges is the following:

Optical components (Laser Optics, Esco Optics and Unique Optics)		$ 213.00
Miscellaneous Laboratories Charges		11.76
	TOTAL	$ 224.76

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$20,488.79	$16,009.21
Retirement	2,674.00	1,358.48	1,315.52
Materials & Supplies	16,950.00	10,410.75	6,539.25
Travel	1,075.00	851.91	223.09
Computer	200.00	-	200.00
Overhead	20,803.00	11,678.60	9,124.40
TOTAL	$78,200.00	$44,788.53	$33,411.47

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
26 November

The following charges have been incurred against the contract during the period 1 October 1973 through 31 October 1973.

Personal Services		$3,091.17
Materials and Supplies		162.80
Overhead and Retirement		1,954.58
	TOTAL	$5,208.55

The breakdown of personal service charges is the following:

J. J. Gallagher		$1,535.36
J. B. Langley		367.18
Technician, Machinists		867.53
Student Assistants		236.00
Administrative Assistance		85.10
	TOTAL	$3,091.17

and supply charges is the following:

Research Gases		$ 78.00
Miscellaneous Laboratories Charges		84.80
	TOTAL	$ 162.80

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$23,579.96	$12,918.04
Retirement	2,674.00	1,551.09	1,122.91
Materials & Supplies	16,950.00	10,573.55	6,376.45
Travel	1,075.00	851.91	223.09
Computer	200.00	-	200.00
Overhead	20,803.00	13,440.57	7,362.43
TOTAL	$78,200.00	$49,997.08	$28,202.92

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
10 December 1973

The following charges have been incurred against the contract during the period 1 November 1973 through 30 November 1973.

Personal Services		$2642.66
Materials and Supplies		236.30
Overhead and Retirement		1749.01
	TOTAL	$4627.97

The breakdown of personal service charges is the following:

J. J. Gallagher		$1077.04
J. B. Langley		316.54
Technician, Machinists		512.55
Student Assistants		542.80
Administrative Assistance		193.73
	TOTAL	$2642.66

and supply charges is the following:

Optical components (laser Optics)		150.00
Miscellaneous Laboratories Charges		86.30
	TOTAL	$ 236.30

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$26,222.62	$10,275.38
Retirement	2,674.00	1,793.78	880.22
Materials & Supplies	16,950.00	10,809.85	6,140.15
Travel	1,075.00	851.91	223.09
Computer	200.00	-	200.00
Overhead	20,803.00	14,946.89	5,856.11
TOTAL	$78,200.00	$54,625.05	$23,574.95

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
28 January 1974

The following charges have been incurred against the contract during the period 1 December 1973 through 31 December 1973.

Personal Services		$3,301.69
Materials and Supplies		169.40
Overhead and Retirement		2,060.45
	TOTAL	$5,531.54

The breakdown of personal service charges is the following:

J. J. Gallagher		$1,512.44
J. B. Langley		126.62
Technician, Machinists		938.55
Student Assistants		564.80
Administrative Assistance		159.28
	TOTAL	$3,301.69

and supply charges is the following:

Research Gases		$ 11.92
Transducer Products		60.00
Miscellaneous Laboratories Charges		97.48
	TOTAL	$ 169.40

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$29,498.00	$ 6,973.69
Retirement	2,674.00	1,972.27	701.73
Materials & Supplies	16,950.00	11,249.25	5,700.75
Travel	1,075.00	851.91	223.09
Computer	200.00	-	200.00
Overhead	20,803.00	16,828.85	3,974.15
TOTAL	$78,200.00	$60,426.59	$17,773.41

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
28 February 1974

The following charges have been incurred against the contract during the period 1 January 1974 through 31 January 1974.

Personal Services		$ 3,183.75
Materials and Supplies		1,286.38
Overhead and Retirement		2,047.38
	TOTAL	$ 6,517.51

The breakdown of personal service charges is the following:

J. J. Gallagher		$ 1,420.78
J. B. Langley		189.92
J. M. Schuchardt		187.25
Technician, Machinists		375.45
Student Assistants		941.45
Administrative Assistance		68.90
	TOTAL	$ 3,183.75

and of supply charges is the following:

Laser Optics, Inc.		$ 455.62
J. A. Noll Optics		285.00
McCoy Optics		384.00
Miscellaneous Laboratories Charges		161.76
	TOTAL	$ 1,286.38

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$32,708.06	$ 3,789.94
Retirement	2,674.00	2,204.91	469.09
Materials & Supplies	16,950.00	12,535.63	4,414.37
Travel	1,075.00	1,051.91	23.09
Computer	200.00	-	200.00
Overhead	20,803.00	18,643.59	2,159.41
TOTAL	$78,200.00	$67.144.10	$11,055.90

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
12 March 1974

The following charges have been incurred against the contract during the period 1 February 1974 through 28 February 1974.

Personal Services		$ 3,185.60
Materials and Supplies		1,286.38
Overhead and Retirement		2,047.38
	TOTAL	$ 6,519.36

The breakdown of personal service charges is the following:

J. J. Gallagher		$ 1,649.94
J. B. Langley		557.11
Technician, Machinists		280.55
Student Assistants		663.55
Administrative Assistance		34.45
	TOTAL	$ 3,185.60

and of supply charges is the following:

Custom Microwaves		$ 650.00
Laser Optics		150.00
Jodon Eng. Assoc.		180.00
Miscellaneous Laboratories Charges		289.75
	TOTAL	$ 1,269.75

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$35,893.66	$ 604.34
Retirement	2,674.00	2,395.51	278.49
Materials and Supplies	16,950.00	13,805.38	3,144.62
Travel	1,075.00	1,071.52	3.48
Computer	200.00	-	200.00
Overhead	20,803.00	20,459.38	343.62
TOTAL	$78,200.00	$73,625.45	$ 4,574.55

COST AND PERFORMANCE REPORT

Contract No DAAB07-73-C-0065
22 April 1974

The following charges have been incurred against the contract during the period 1 March 1974 through 31 March 1974.

Personal Services		$3,130.26
Materials and Supplies		6,500.04
Overhead and Retirement		1,998.62
Travel		214.87
	TOTAL	$11,843.69

The breakdown of personal service charges is the following:

J. J. Gallagher		$1,352.03
J. B. Langley		835.67
Technician, Machinists		394.71
Student Assistants		513.40
Administrative Assistance		34.45
	TOTAL	$3,130.26

and supply charges is the following:

Optoelectronics Detectors		$6,180.00
General Scanning Mirror		225.00
Research Gases		49.00
Miscellaneous Laboratories Charges		46 04
	TOTAL	$6,500.04

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$36,498.00	$39,023.92	$-2,525.92
Retirement	2,674.00	2,609.88	64.12
Materials & Supplies	16,950.00	20,305.42	-3,355.42
Travel	1,075.00	1,286.39	- 211.39
Computer	200.00	-	200.00
Overhead	20,803.00	22,243.63	-1,440.63
TOTAL	$78,200.00	$75,469.24	$-7,269.24

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
28 May 1974

The following charges have been incurred against the contract during the period 1 April 1974 through 30 April 1974.

Personal Services		$2,916.88
Materials and Supplies		1,224.02
Overhead and Retirement		1,885.05
	TOTAL	$6.026.95

The breakdown of personal service charges is the following:

J. J.Gallagher		$1,397.86
J. B. Langley		785.02
Technician, Machinists		207.35
Student Assistants		564.80
Administrative Assistance		526.65
	TOTAL	$2,916.88

and supply charges is the following:

Cleveland Crystals		$1,095.00
Laser Optics		100.66
Miscellaneous Laboratories Charges		28.36
	TOTAL	$1,224.02

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$46,930.00	$41,940.80	$ 4,989.20
Retirement	3,310.00	2,832.31	477.69
Materials & Supplies	23,510.00	21,529.44	1,980.56
Travel	1,075.00	1,286.39	- 211.39
Computer	200.00	-	200.00
Overhead	27,584.00	23,906.25	3,677.75
Total	$102,609.00	$91,495.19	$11,113.81

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
18 June 1974

The following charges have been incurred against the contract during the period 1 May 1974 through 30 May 1974

Personal Services		$4,017.42
Materials and Supplies		1,439.84
Overhead and Retirement		3,047.83
	TOTAL	$8,505.09

The breakdown of personal service charges is the following:

J. J. Gallagher		$1,993.67
J. B. Langley		974.94
Technician, Machinists		232.98
Student Assistants		743.40
Administrative Assistance		72.43
	TOTAL	$4,017.42

and supply charges is the following:

II-IV, Inc.		$ 285.00
Laser Optics		580.00
Oriel Optics		450.00
Miscellaneous Laboratories Charges		124.84
	TOTAL	$1,439.84

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$46,930.00	$45,958.22	$ 971.78
Retirement	3,310.00	3,035.47	274.53
Materials & Supplies	23,510.00	22,969.28	540.72
Travel	1,075.00	1,286.39	- 211.39
Computer	200.00	-	200.00
Overhead	27,584.00	26,750.92	833.08
TOTAL	$102,609.00	$100,000.28	$2,608.72

COST AND PERFORMANCE REPORT

Contract No. DAAB07-73-C-0065
26 July 1974

The following charges have been incurred against the contract during the period 1 June 1974 through 30 June 1974.

Personal Services		$1,191.45
Materials and Supplies		190.40
Overhead and Retirement		1,052.73
	TOTAL	$2,434.58

The breakdown of personal service charges is the following:

Technician, Machinists		$ 81.40
Student Assistants		1,110.05
	TOTAL	$1,191.45

and supply charges is the following:

Photo Lab (Report)		$ 122.77
Consolidated Ceramics		50.00
Miscellaneous Laboratories Charges		17.63
	TOTAL	$ 190.40

The current financial status of the contract is the following:

	Budget	Expended	Free Balance
Personal Services	$46,930.00	$47,144.67	-$219.67
Retirement	3,310.00	3,313.76	- 3.76
Materials & Supplies	23,510.00	23,159.68	350.32
Travel	1,075.00	1,286.39	- 211.39
Computer	200.00	-	200.00
Overhead	27,584.00	27,525.36	58.64
Total	$102,609.00	$91,495.19	$ 179.05

COST AND PERFORMANCE REPORT NO. 22

Contract No. DAAB07-73-C-0065
28 January 1975

The following charges have been incurred against the contract during the period 1 September 1974 through 30 September 1974.

Materials and Supplies		$3.70
	TOTAL	$3.70

No personal charges were incurred during September.

The current financial status of the contract is the following.

	Budget	Expended	Free Balance
Personal Services	$46,930.00	$47,174.99	-$244.99
Retirement	3,310.00	3,322.90	- 12.90
Materials & Supplies	23,510.00	23,809.10	- 299.10
Travel	1,075.00	1,286.39	- 211.39
Computer	200.00	-	200.00
Overhead	27,584.00	27,541.82	42.18
TOTAL	$102,609.00	$103,135.20	-$526.20

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

ECOM-0065-2

MINIATURE MOLECULAR FREQUENCY SOURCE

SECOND INTERIM TECHNICAL REPORT

By

J. J. Gallagher

DECEMBER 1973

DISTRIBUTION STATEMENT
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ECOM

UNITED STATES ARMY ELECTRONICS COMMAND • FORT MONMOUTH, N.J.

Contract DAAB07-73-C-0065

Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia

TECHNICAL REPORT ECOM-0065-2
December 1973

MINIATURE MOLECULAR FREQUENCY SOURCE

SECOND INTERIM TECHNICAL REPORT

15 June 1973 to 15 December 1973

CONTRACT NO. DAAB07-73-C-0065

DA PROJECT NO. 15662705A05803

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Prepared by

J. J. Gallagher

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

For

U. S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, N. J.

NOTICES

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FOREWORD

This report was prepared by the Engineering Experiment Station at Georgia Tech under Contract No. DAAB07-73-C-0065. The work described was performed in the Systems and Techniques Department and was conducted under the supervision of Mr. J. J. Gallagher, Project Director. The report summarizes the objectives and activities of the second six month period of the program. The overall objective of the program is the development of a miniature stable CO_2 molecular laser.

The contributions of W. Penn, J. Langley, B. McManus, and W. D. Fife of the Georgia Tech staff are acknowledged.

ABSTRACT

Investigations performed on a miniature molecular frequency source are discussed. The work on the small laser and each component required for the stabilization of the source is described. The final system, as it is planned, is described. For the projected 50 mW output of the laser, calculations indicate that this is sufficient power for the control system. Work toward laboratory observations of the fluorescence signals is discussed.

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1. Introduction

This report discusses the work performed during the second six month period on Contract No. DAAB07-73-C-0065. The objective of this program is the development of a miniature stable CO_2 laser whose CW output can eventually serve as the reference for a stable 5 MHz frequency source once the necessary multiplier chain becomes available. The stabilized source was described in the First Interim Technical Report and the design goals were given in Appendix I of that report.

During the second interim period, investigations have been performed on all aspects and individual components of the system which will eventually be assembled as the molecular source. In addition, laboratory experiments are being performed on the 4.3 μm fluorescence which is employed for the stabilization of the CO_2 laser.

In the sections which follow, investigations performed on the individual components are described. Problems encountered and the anticipated performance in the system which will be assembled are discussed. The projected design of the overall system is presented in Section 9, while laboratory investigations on 4.3 μm fluorescence are discussed in Section 10.

2. External Modulation

The use of an external frequency modulator is necessitated by the requirement to maintain the laser output signal free of modulation. The possible use of an external electro-optic phase modulator has been discussed in the First Interim Report, and it was shown that the low power requirements of our design goals render an electro-optic device impractical.

The use of a moving mirror modulator has been shown elsewhere [1], and this technique has been investigated in detail during the past interim period. The small size and low power restrictions have introduced problems, mainly on mechanical stability, into the apparatus.

For the investigation of a small mirror moving device, several elements have been studied. These have included earphone speakers, piezoelectric bimorphs, solenoids and conventional miniature speakers. The earphone element cannot provide sufficient displacement, while the bimorph and solenoids are unstable and consume excess power for operation. The small speaker has provided the best operation thus far. Initially, one small element with the cone cut away has been shown to produce mirror translations in excess of a millimeter, but considerable "wobble" of the mirror has been present during the motions. The motion of the mirror has been studied by using the moving element as one of the mirrors in a Michelson interferometer employing an argon laser. A resonance in the motion exists at approximately 150 Hz. Relatively small power consumption was required for this motion. Approximately 72 milliwatts drove the mirror. Further power reduction is possible when the speaker coil is resonated.

In order to minimize the "wobble", a modulator employing a moving mirror mounted on a speaker and held aligned with telescopic tubing has been constructed. The device has shown greater stability than previous configurations but has its optimum vibrations at a low frequency ($\sim$ 105 Hz). Approximately 3 mm displacement is achieved at power levels on the order of that used with the initial units. Some small play in the telescopic tubing results in the instability that remains. Tighter fitting tubing will cause additional friction, resulting in increased power consumption.

As an alternate scheme, a system, consisting of a General Scanning Model G-124 Optical Scanner in conjunction with a stepped mirror is being studied. Figure 1 shows the manner in which a signal reflected off a stepped mirror will result in a square-wave modulated signal. The signal reflected from the rotating scanner element is moved from one piece of the stepped mirror to the other. The step depth required is approximately 0.50 mm to provide the frequency modulation necessary for the laser control system. The technique should overcome vibrations and instability present in the other device, but it does result in two beams separated by approximately 2.5 mm. Shaping of the stepped mirror is being considered for reduction of this separation. In the case of the technique employing a single moving mirror, the angle of incidence must be small to avoid both separation of the beams and the need for large mirror displacements.

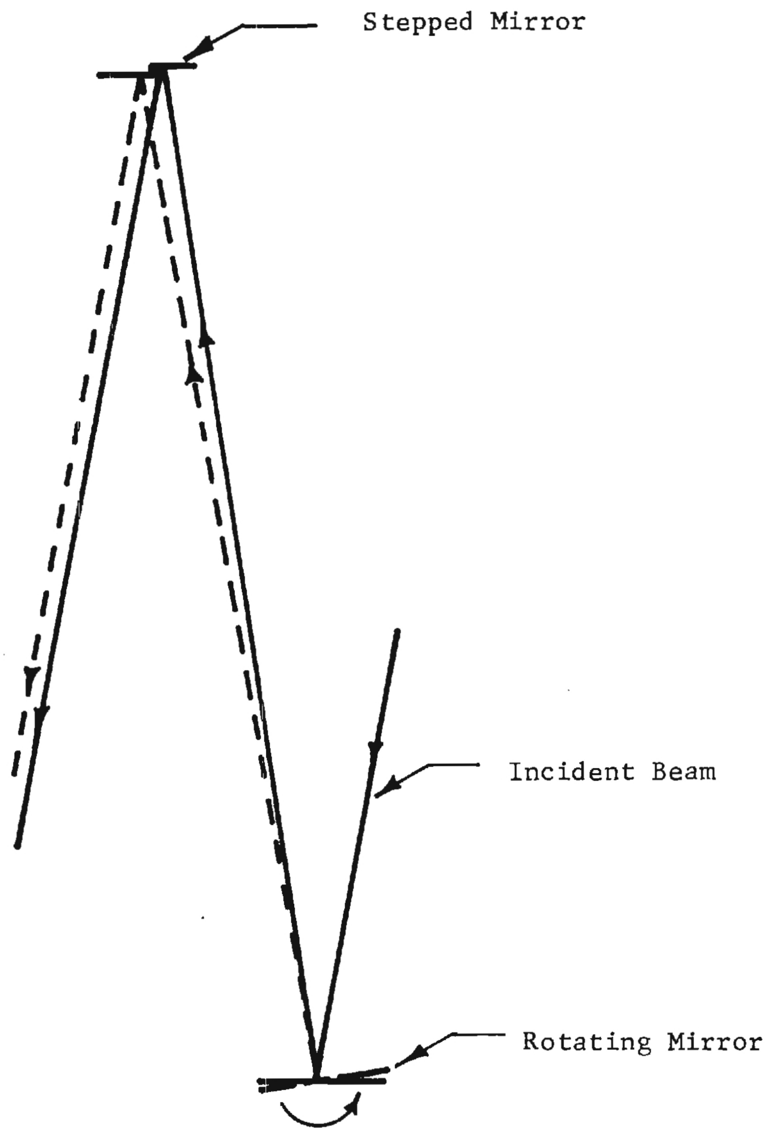

Figure 1. Frequency Modulator Employing Rotating Mirror and Stepped Mirror.

3. External Control Cell

The stable source will employ an external fluorescence cell in order to avoid modulation of the laser and effects of gases other than the laser medium. Originally, a 1 inch diameter cylindrical cell approximately 2 inches long was to be employed as the control cell. This cell was to have room temperature PbSe detectors on each side of the cell. Because of the lowering of the power density by expanding to a diameter of 1 inch, a cell with a diameter of approximately ½ inch and a 3 inch length will be employed. Figure 2 shows a sketch of the control cell. The 20 detector elements can be employed with this cell. The CO_2 pressure in the cell will be held at approximately 125 millitorr to yield the fluorescence signal strength calculated in the First Interim Report.

During the past reporting period, a fluorescence cell has been constructed to be used for the laboratory tests. The cell is constructed from invar, is 2 inches in length, 1 inch in diameter. The inside walls are gold-plated. A salt window serves as an entrance port and a gold mirror serves as the back wall. The cell is mounted on an aligning apparatus which will serve to adjust the cell for a standing wave. A sapphire window on the side of the cell permits observations of the 4.3 μm fluorescence with an InSb detector (77°K) or a thermoelectrically cooled PbSe detector. For use with the room temperature PbSe detector, the sides can be bored out. The 3 inch long cells, which will eventually be employed, will be bored out of either invar or ULE quartz.

4. Laser Source

During the past reporting period, investigations have been performed on the miniature CO_2 laser. The goal is to provide sealed-off lasers, approximately 2-3 inches in length. Single mode, single line operation is required with no water cooling. Waveguide lasers cannot be employed since the waveguide laser requires greater power input, operates at high pressure and the waveguide structure can support more than one mode.

In the First Interim Report, structures, constructed out of ULE quartz, were described. Poor vendor deliveries have resulted in delays in testing

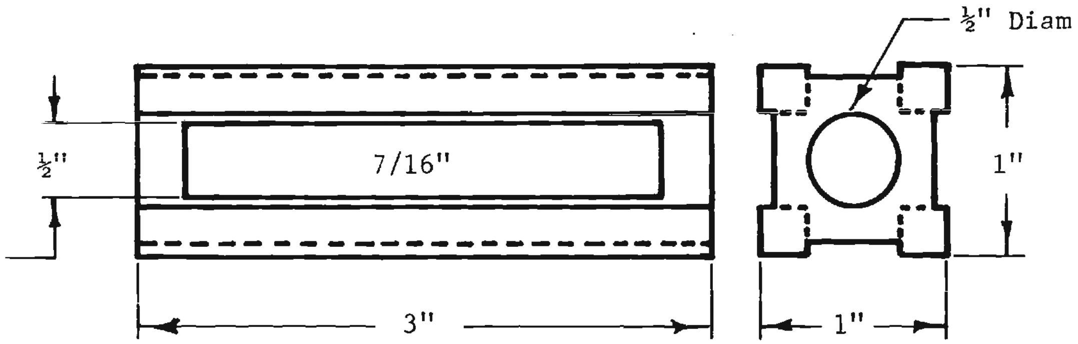

Figure 2. External Control Cell.

these units. In the initial tests, the units did not lase; despite the low input powers, poor heat dissipation is suspected as the cause. The two small ULE quartz cylinders described in the First Interim Report have been tested at a variety of pressures and voltages. A discharge in the small unit can be maintained at an input of only 0.42 watts (0.7 ma at 600 volts), but, even at these low inputs, heating is a problem. Tests continue on the largest ULE resonator (2" diameter x 3.15" length) with electrode configurations which can serve as heat sinks. The cells have a flat mirror and a Ge mirror with radius of curvature of ½ meter with 90% reflectivity. Cylindrical piezoelectric transducers are now available to drive a mirror.

In order to achieve laser action in these small tubes, several options are now being considered. An ultrasonic drill and diamond rotary burrs are available to drill the ULE quartz frames. The ULE quartz and invar are being employed to serve as the resonators for the short lasers with alumina and beryllia being used as the laser tubes. Proper heat sinking of the alumina or beryllia should result in the laser walls being sufficiently cool for lasing to occur.

The following units can now be assembled and tested:

1) The large ULE quartz resonator, 2" diameter and 3.15" length, can have its center tube (0.625" OD, 0.250" ID) bored out and replaced by an alumina tube. In this configuration, shown in Figure 3, the anode can serve as a heat sink for the alumina; the device can operate either with the alumina tube in vacuum or sealed so that air serves to conduct heat from it. The ULE quartz will provide a stable resonator for the laser.

2) Both small ULE cylinders are being bored out to have alumina tubes inserted and heat sinks provided for the tubes.

3) An invar frame has been machined and the ends have been optically polished. This frame will be tested as a resonator for the miniature laser. The cathode is attached to the invar while the anode is a copper section, insulated from the invar and holding a Brewster's angle window. The Brewster's angle window is currently sodium chloride. Alumina is being employed as the laser tube. This configuration is shown in Figure 4.

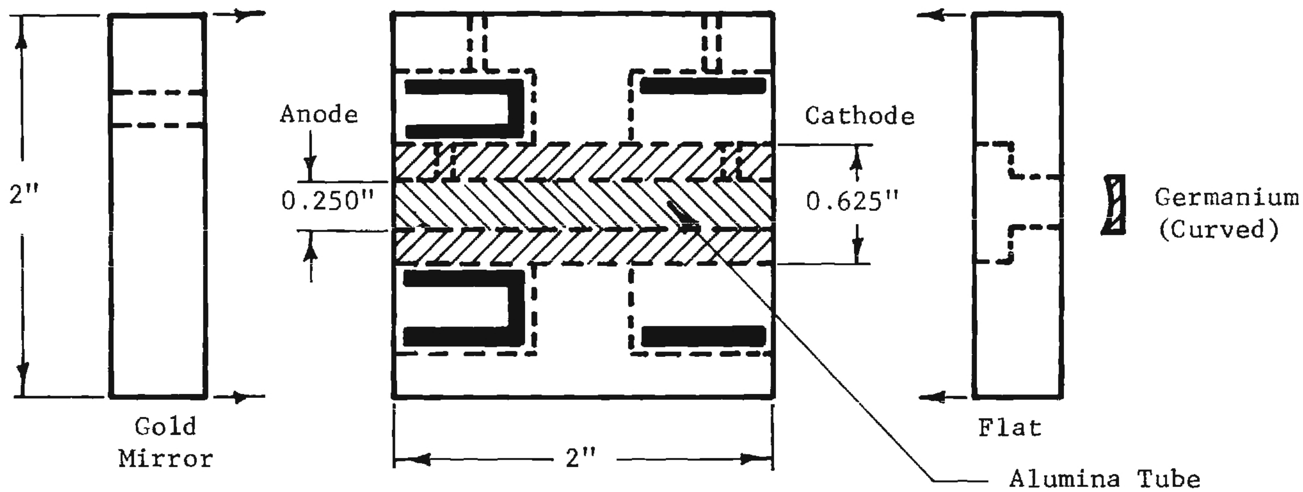

Figure 3. ULE Quartz Cavity with Alumina Tube.

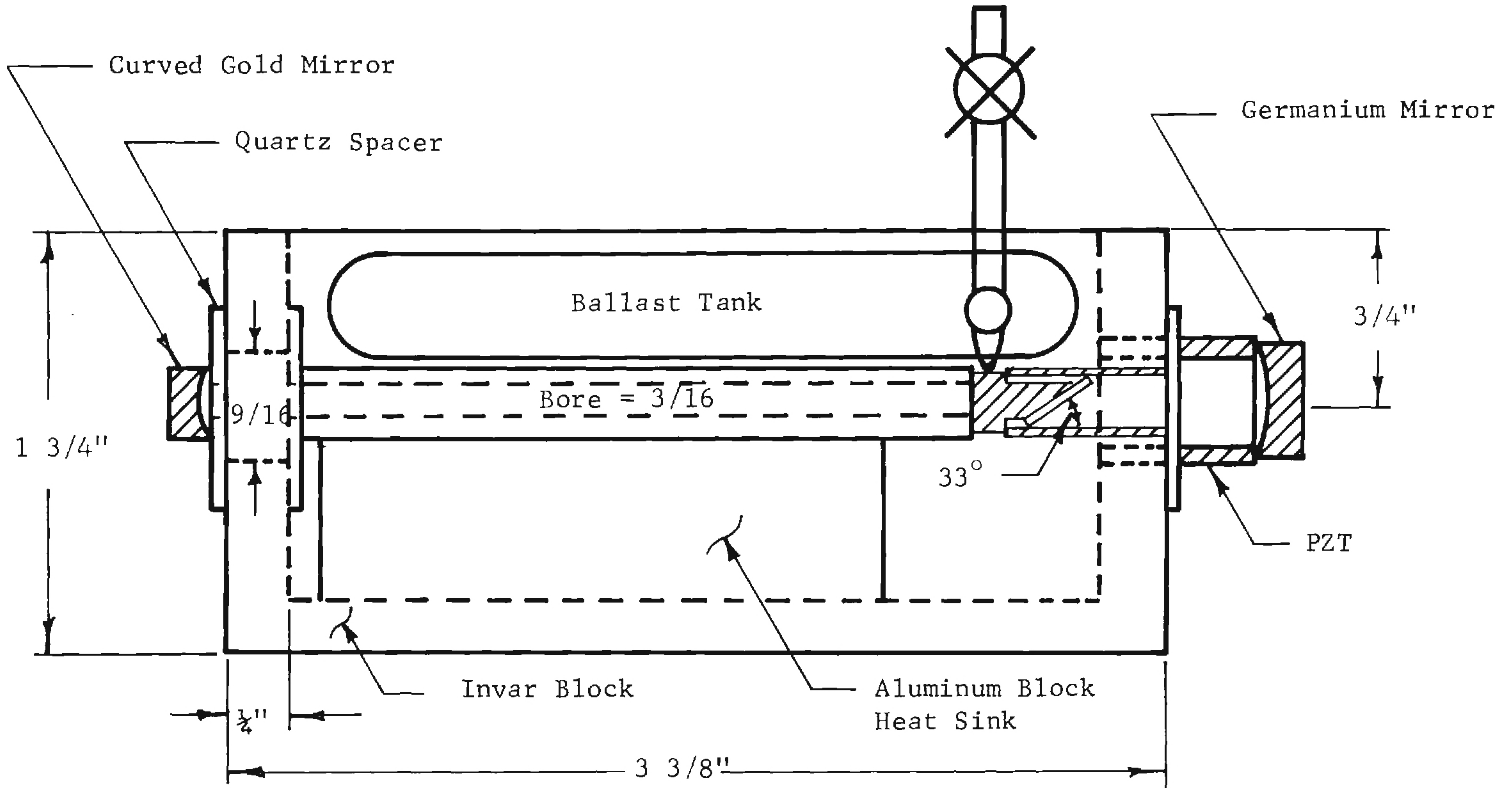

Figure 4. Invar Block CO_2 Laser.

4) Two small beryllia tube lasers are currently being tested. One, shown in Figure 5, employs three electrodes (two end anodes and a center cathode), has a bore of approximately 0.250 inch and is on the order of 3.250 inches long. Mirrors employed are a total reflecting flat and a ½ meter radius of curvature 90% reflecting Ge mirror. The other, with an electrode at each end, has a 2 mm bore, is approximately 2 inches long and has the same mirror arrangement. With the latter configuration, damage to the gold total reflector will have to be avoided. Because of the low gain in these short tubes, an increase of the reflectivity of the output mirror to approximately 96% is being considered.

5. Beam Splitter/Isolator

To provide a useful output signal for frequency measurements and simultaneously a signal for locking the laser, a beam splitter is required. By using the beam splitter at the Brewster's angle, it can be used as part of an isolator which is necessary to protect the laser from return signals from the control apparatus. The polarized reflected signal from the Brewster plate is passed through a quarter wave plate before entering the control cell. The circularly polarized return signal is eliminated by the quarter wave plate-polarizer combination.

For the apparatus which will be assembled during the next six month period, a germanium beam splitter will be employed. With an index of refraction of 4.00, the germanium Brewster's angle θ_B is approximately 76°. The reflected polarized power is on the order of 40 percent of the laser output. The quarter wave plate which will be employed is a CdTe plate on the order of 1 millimeter thick. If a Brewster's angle laser is employed as shown in Figure 4, then the beam splitter can be used at any chosen angle.

6. Detectors

The detection of the 4.3 μm fluorescence in the molecular frequency source must be performed by room temperature detectors. The most advantageous room temperature detector at the fluorescent wavelength is PbSe.

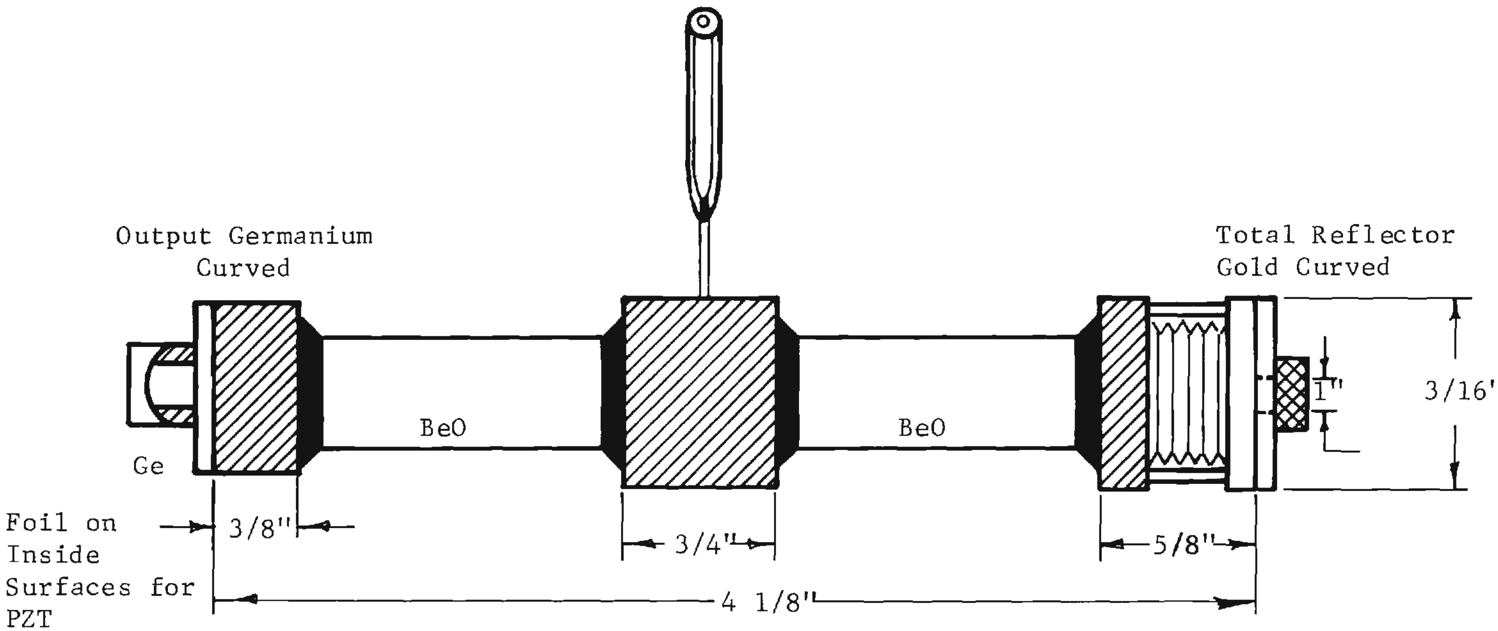

Figure 5. Beryllia Tube Laser with Center Cathode.

The calculations performed in the First Interim Report indicate that an array of detectors covering the sides of the control cell would be the optimum arrangement. Quotes have been received from two vendors, and a third is being considered. The detector arrangements recommended by the manufacturers would consist of several detectors on each side. The manufacturers recommend the use of a single thermoelectrically cooled PbSe detector on each side as being superior to the room temperature arrays; however, the power consumption for the thermoelectric elements far exceeds the power allowed for operation of the system. With the cell shown in Figure 2, an array of five detectors on each side can be employed. This configuration is shown in Figure 6. By employing reflective surfaces on two sides, only 10 detectors, five on each of the remaining two sides, might be necessary.

7. Optics of the System

The laser signal, which is used to control the laser externally, must be modulated, collimated and expanded before entering the fluorescence cell. Figure 7 shows a sketch of the laser system which is being planned and will be assembled during the next period. The beam splitter, isolator, modulator and control cell have been described.

For collimation of the beam, three methods have been investigated. Parabolic reflectors with either a secondary parabolic mirror (Reference 2) or a diverging lens (Reference 3) as the feed have been studied. Both are practical for the system to be employed. A lens combination, in the form of a Galilean telescope, will be used, however, because of the ease of alignment. The costs are comparable for the three systems considered. With the small space available, the beam expansion from a 2 mm diameter to one of approximately 12.5 mm will be done in a length on the order of 3 inches. The telescope will consist of an $f = 1$ diverging lens with a focal length of ½ inch and an $f \approx 3$ concave lens with a focal length of approximately 3.125 inches.

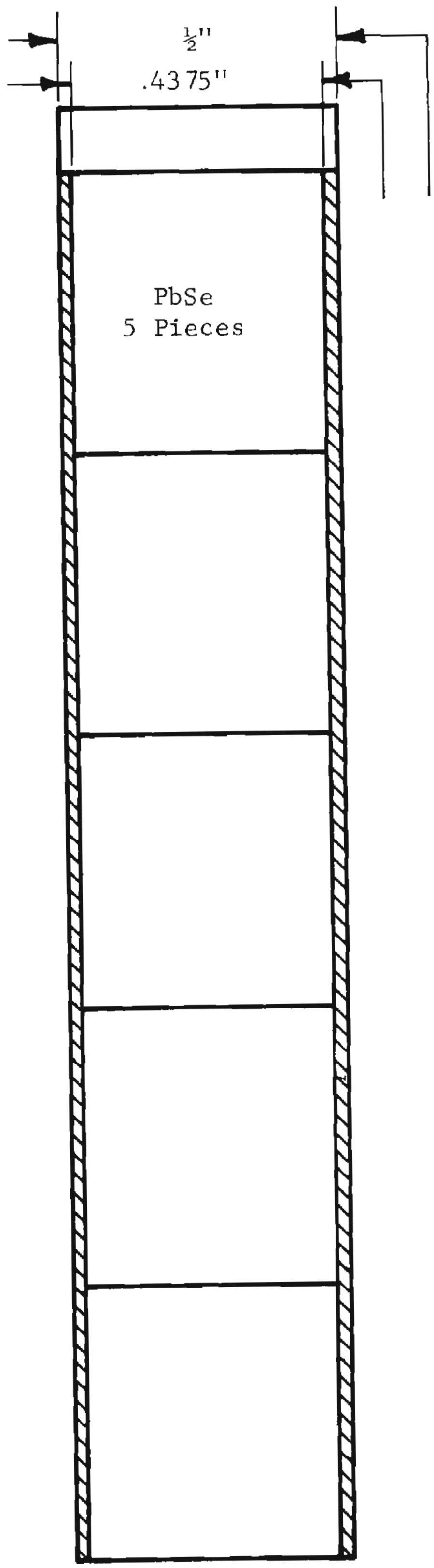

Figure 6. PbSe Detector Elements 0.4375" x 0.500" 5 Elements/Side.

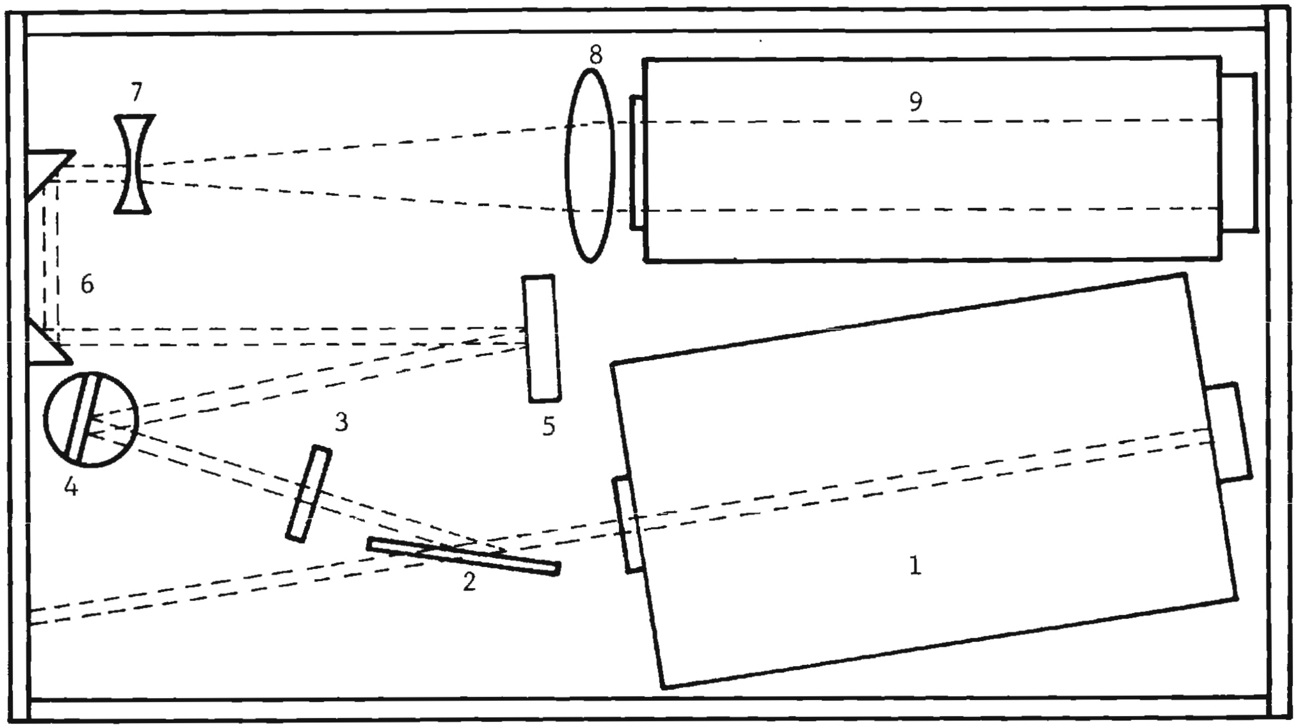

Figure 7. Miniature Molecular Frequency Source (1 Indicates CO_2 Laser and 9 Indicates the Control Cell. Individual Components are Described in the Text.)

8. The Stabilized Molecular Source

The molecular frequency source which will be assembled during the next period is sketched in Figure 7. It will employ the components which have been discussed in the previous sections. As it is shown, the system includes the 3 inch long invar block laser (1), the cross-section of which is 1.75 inches by 1.75 inches. The 3 inch long fluorescence control cell (9) is employed.

In Figure 7, the optical arrangement is the following: the signal from the laser (1) is split by the germanium beam splitter (2), which is oriented at the Brewster's angle, θ_B, which is 76°. The useful output passes through the beam splitter, while the control signal, reflected from the plate, passes through the CdTe $\lambda/4$ plate (3). The modulator consists of a rotating mirror (4) and the stepped reflector (5). After reflection from mirror (6), the signal is collimated and expanded by lenses (7) and (8) to enter the control cell (9). A rear reflector serves to return the signal through the cell to establish a standing wave. The signal reflected from the Brewster's angle plate will be approximately 40% of the laser output. Including additional losses in mirrors, lenses and windows, approximately 35% of the laser output will reach the control cell. When the beam diameter is expanded from 2 mm to 12.5 mm, there results a power density reduction by a factor of approximately 39.

With a height on the order of 1.75 inches, the volume of the molecular source is approximately 2.5 times larger than the original design goal of 20 cubic inches. This can be reduced by narrowing the width slightly and by reducing the height. The height of the unit is determined by the cross-section (1.75 inches x 1.75 inches) of the invar laser resonator. All other components are on the order of approximately 1.0 inch in height. Reduction in the height can thus result in further volume reduction.

Further reduction of the size of the source is limited by the optics and the length of the control cell. The requirement to expand the beam from approximately 2 mm to 12.5 mm necessitates a telescope arrangement (lenses 7 and 8) with a focal length of about 3 inches. The use of a multipass control cell or a confocal resonator could lessen the volume of the control cell, but the multipass cell would not provide a standing wave and, with the low power which will be available, coupling into the resonator would result in excessive losses.

For a laser with approximately 50 mW output, about 18 mW will reach the control cell. This power will be expanded to fill the ½ inch diameter control cell. Under these conditions, the intensity is 147 watts per $(\text{meter})^2$. This corresponds to $E^2 = 12.27 \times 10^4\ (V/m)^2$ since

$$I = \frac{\epsilon_o c E^2}{2} \text{ watts}/(\text{meter})^2$$

where $\epsilon_o = 8.854 \times 10^{-12}$ Farads/m and c is the velocity of light. That this is sufficient input power to the control cell to result in detectable saturated 4.3 μm fluorescence can be seen from Equation (16) of the First Interim Report

$$P_F = \frac{2\hbar W_F \sqrt{\pi}}{4\pi\, ku} \left(\frac{x^2\gamma}{\Delta\omega}\right) \Omega_F\, \eta_F\, V\, \Delta N^o$$

or

$$P_F = \frac{\hbar W_F}{2\sqrt{\pi}\, ku} \left(\frac{x^2\gamma\tau}{\Delta\omega}\right) \frac{\Omega_F\, \eta_F\, V\, \Delta N^o}{\tau}$$

Calculating x^2 from the electric field corresponding to 18 mW from the laser yields

$$x^2 = 2.1 \times 10^{12}\ (\text{Hz})^2$$

so that $x^2 > \gamma/2\tau$ which can be assumed to occur in saturation. When the values for the various factors are put into P_F, the equation equivalent to Equation (17) of the First Interim Report is obtained for the input power of 18 mW. That is

$$P_F = 238 \times 10^{-29}\ \Omega_F\, \eta_F\, V\, \Delta N^o\, \gamma/\tau \text{ watts}$$

This corresponds to an increase of power by a factor in excess of 100 over that calculated in Equation (17) of the First Interim Report. As a result, a smaller volume can be employed with a resulting increase in power over the previous estimate.

If a volume which is only 29% of the original volume is used, as presently planned with the 3 inch cell, then this fluorescent level is on the order of 30 times larger than the original signal and should be detected with the planned system. The estimated strength of the Javan-Freed signal is also increased by this value for the same experimental values. Since the S/N ratio was estimated from a comparison with the Javan-Freed signal, no overall increase in signal to noise ratio is expected.

9. Laboratory Laser

The laser shown in Figure 8 is being employed for control experiments presently being performed in the laboratory. The overall length of the laser is 61 cm. The laser mirrors, mounted in the end plates which are separated by three invar rods, are a germanium flat with 80% reflectivity and a maximum reflectivity (gold plated quartz) curved mirror with radius of curvature of 1 meter. The maximum reflector is mounted on a piezoelectric translator which changes the laser length and provides the means for modulating the laser. The control cell is a stainless steel chamber, placed internal to the laser, with a sapphire window for observation of the 4.3 μm fluorescence. A salt window at the Brewster's angle separates the laser from the control cell. The bore of the laser is approximately 10 mm while the discharge length is 28 cm. Approximately 2 watts maximum power is obtained from this laser.

The laser has operated single mode and single line at low power levels; however, some mode changes have occurred during lasing resulting in TEM_{10} mode outputs and oscillation at the P(20) and P(18) wavelengths.

A pair of apertures of 5 mm diameter has been inserted in the laser tube to yield a Fresnal number on the order of one. This yields diffraction losses of 0.6% for the TEM_{00} mode and 7% for the TEM_{10} mode. The calculated

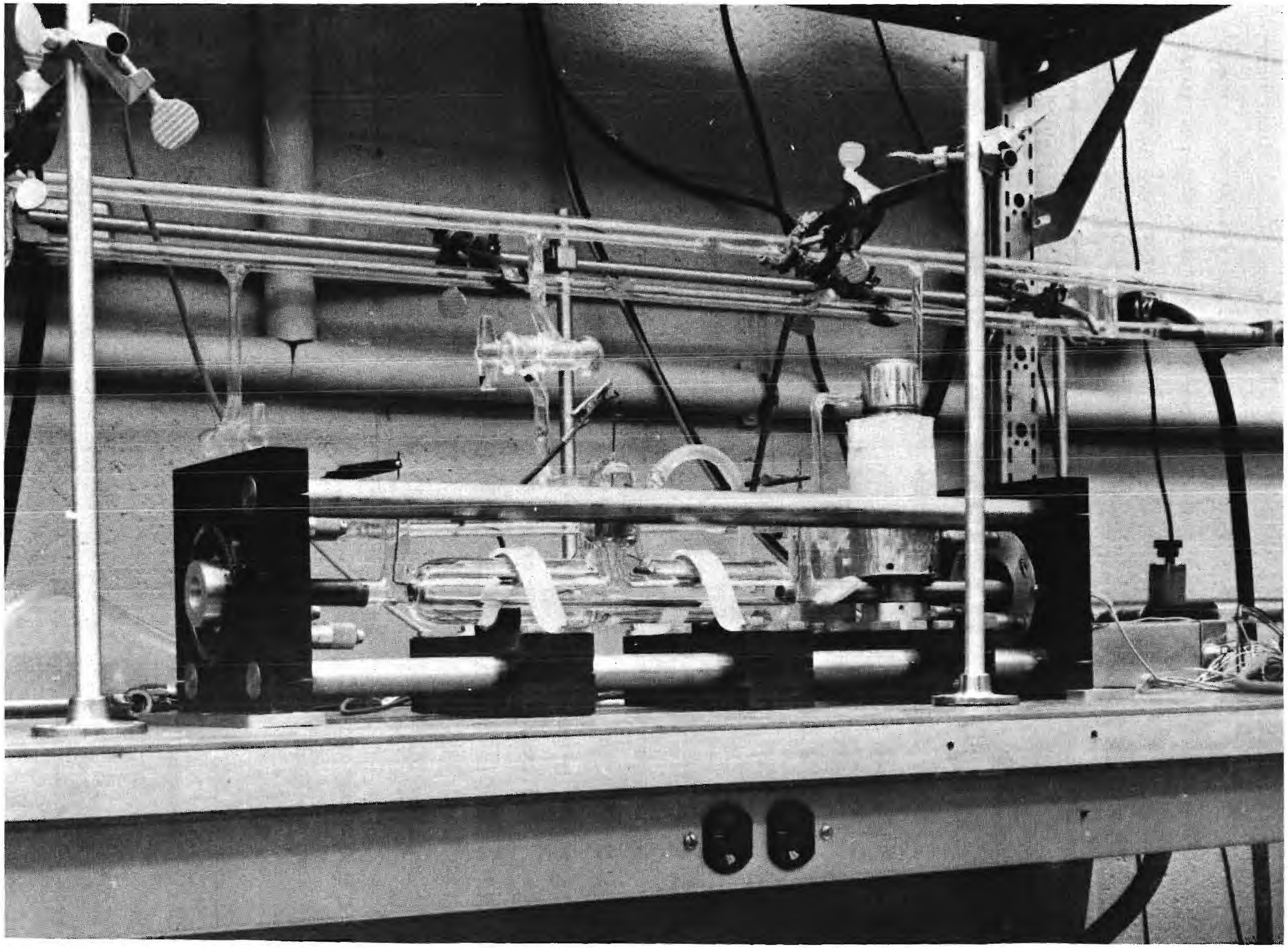

Figure 8. Laboratory Lasser with Internal Control Cell.

output power for this configuration is $P_{out} \approx 4$ watts [4]. Operation under these conditions has resulted in single mode, single line operation. The study of mode structure continues for use in the fluorescence observations.

The 4.3 μm fluorescence is observed by an InSb detector cooled to $77^{\circ}K$. Modulation at 200 Hz and 520 Hz has been employed. The use of a narrowband filter, centered at 4.3 μm, is necessary. This filter, which is external to the dewar, must be cooled. A more desirable configuration would be to have the filter inside the dewar. In the initial observations, considerable electrical noise existed. Improved shielding has resulted in a reduction of the noise level. Fluorescence at 4.3 μm has been observed with this apparatus. The Lamb dip was not evident on this fluorescence output, but, with the mode improvements mentioned above, the dip should now be observable. The external cell which has been constructed can be employed with this laser.

10. Heterodyning Device

For the frequency comparison of the three molecular sources which will be constructed during the final six months, the heterodyning will be performed in two different mixers. One will be the HgTe, CdTe detector which is presently being employed for laboratory tests. The other unit is a metal-oxide-metal diode which allows room temperature operation and could be employed for heterodyning in the field.

The metal-oxide-metal diode which is fabricated by E. Horvath (Custom Microwaves) meet the heterodyning requirements which we have. One of these units, along with one dozen whiskers, are being obtained from Horvath and will be available in February.

11. Discussion of Future Work and Conclusions

During the next reporting period, the system which has been described will be assembled. The major problems exist in the operation of a small uncooled CO_2 laser and the use of the proper configuration of room temperature PbSe detectors to observe the Lamb dip in fluorescence.

The various small laser configurations which have been described will be investigated. Three of these units will be constructed and heterodyned while the system is being assembled. The scanner-stepped mirror modulator presently offers the best arrangement for modulating the beam at a 200 Hz rate. Reduction of vibrational effects and removal of the "wobble" experienced in other devices should result. Currently, determinations are being made to establish the effects of the modulator on the laser beam size and shape.

The dissipation of heat from the small CO_2 lasers presents a problem which will have to be solved. The use of beryllia or alumina tubes with ULE quartz or invar for the resonators is expected to solve this problem.

The beam expander will be the lens combination described above, although calculations are being performed to compare this technique with the off-axis parabola configurations also described above.

The 4.3 µm detectors which will be employed will be the room temperature PbSe arrays which have been described above. Detector vendors have stated that thermoelectrically cooled PbSe detectors would be preferable but the power consumption in the coolers far exceeds the specified input power of the design goals.

The size of the planned apparatus still exceeds the 20 cubic inches which is the goal for the units. This limitation is imposed by the optics of the system. Studies will continue toward reducing the size shown in Figure 7.

The laboratory tests on fluorescence will continue. An improved detector, with internal filter, will be obtained. That will provide improved operation and remove the cumbersome procedure of cooling the external filter. The investigations will include observations with both internal and external control cells.

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4. T. S. Fahlen, Appl. Optics 12, 2381 (1973).

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13. ABSTRACT

Investigations performed on a miniature molecular frequency source are discussed. The work on the small laser and each component required for the stabilization of the source is described. The final system, as it is planned, is described. For the projected 50 mW output of the laser, calculations indicate that this is sufficient power for the control system. Work toward laboratory observations of the fluorescence signals is discussed.

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

ECOM–73–0065–F

MINIATURE MOLECULAR FREQUENCY SOURCE

By

J. J. Gallagher
Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
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February 1976

Final Report, for Period 15 November 1972 to 15 August 1974

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An investigation has been performed to determine the characteristics of a miniature stabilized CO_2 laser. The investigation included studies of miniature CO_2 lasers, external frequency modulators, and room temperature 4.3 μm detectors. Lamb dip observations in the 4.3 μm fluorescence of CO_2 have been detected with a 77°K InSb detector employing both internal and external fluorescence cells. A small molecular frequency source has been assembled. The critical design parameters for miniature molecular sources are discussed. Small normal mode

CO_2 lasers (both water cooled and room temperature) have been constructed with resonator lengths of 6 inches and efficiencies in the range of 7.5 - 10%.

ECOM-73-0065-F

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Atlanta, Georgia 30332

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FOREWORD

This report was prepared by the Engineering Experiment Station at Georgia Tech under Contract No. DAAB07-73-C-0065. The work described was performed in the Systems and Techniques Department and was conducted under the supervision of Mr. J. J. Gallagher, Project Director. The report summarizes the objectives and activities of the program. The overall objective of the program is the development of a miniature stable CO_2 molecular laser at the request of and as specified by the U. S. Army Electronics Technology and Devices Laboratory (ECOM).

The assistance and technical advice of Dr. Erick Hafner, contract monitor, are gratefully acknowledged. The contributions of W. Penn, J. Langley, B. McManus, and W. D. Fife of the Georgia Tech staff are acknowledged.

1. Introduction

This report discusses the work performed on Contract No. DAAB07-73-C-0065, entitled "Miniature Molecular Frequency Source." The objective of this program has been the development of a miniature stable CO_2 laser whose CW output can eventually serve as the reference for a stable 5 MHz frequency source once the necessary multiplier chain becomes available. The design goals for such a device are given in Appendix I of the First Interim Technical Report. For the system investigated under this program, it is required that the CO_2 laser be miniaturized, the fluorescence control cell placed external to the laser resonator, the modulation of the signal be performed externally and a room temperature detector system be employed. The investigation considered the feasibility of the apparatus volume being approximately 20 cubic inches with power consumption on the order of 1 watt, and the open loop short term stability to be 1 part in 10^{13} or better for integration times of 0.1 sec. The stabilization technique investigated is one which has been successfully demonstrated by Javan and Freed [1].

During the program, all aspects of the miniature CO_2 frequency source have been investigated. Significant contributions have been made to the understanding and eventual development of a miniature stable laser source. None of the design goals have been shown to be infeasible despite the difficulty encountered in developing the individual components. Continued investigation of many of the elements treated in this program is necessary before a complete evaluation of some of the goals can be made.

In the following sections of this report, a description is given of the several areas studied during the course of the program. In Section 2, observations on the Lamb dip in the 4.3 μm fluorescence of CO_2 are described and related to the application to the miniature molecular source. In succeeding sections, operation of small lasers (Section 3) is discussed, studies of external modulation (Section 4) are treated, and the components necessary for a miniature system are described. Three miniature systems (Section 8) have been assembled. The units which have been assembled are so constructed that individual elements can be replaced as advances are made.

The major problems involved in a small system are the power consumption and the operation of room temperature detectors. In Section 10, the conclusions which can be drawn from this work are presented, and recommendations which will contribute to the development of the individual components are given.

2. Lamb Dip Observations

The Lamb dip in the 4.3 μm fluorescence of CO_2 was observed during the course of the program in fluorescence cells which were both internal and external to the CO_2 laser. The fluorescence was detected with InSb photovoltaic detectors, cooled to 77°K. The laboratory laser which was employed for the observations was described in the Second Interim Report and shown in Figure 8 of that report. Several factors pertinent to the low power saturation necessary for a miniature molecular frequency source are evident from these observations.

In the initial attempts to observe the Lamb dip, difficulties were experienced. The major cause of the inability to observe the dip was the 4.3 μm detector used with the internal cell. The internal cell is also shown in Figure 8 of the Second Interim Report. The observing detector initially used was an InSb detector cooled to 77°K. A filter, centered at 4.3 μm was external to the dewar and required cooling. Inconsistency resulted from the instability of the cooling process. Fluorescence was observed with this arrangement but the Lamb dip was not evident in the fluorescence output. Thermal shielding was required for the InSb detector. In order to provide a background on the order of 77°K, the construction of a shield with the control cell and 4.3 μm filter was necessary. The region between the detector and control cell required flushing with liquid and dry nitrogen. The liquid nitrogen cooled the narrow band filter and the dry nitrogen prevented moisture formation and cooling of the fluorescence cell. A mirror at the bottom of the cell [1] permits the detector to see a 77°K background. A sapphire window in the top of the control cell transmits the 4.3 μm fluorescence. Electrical shielding from sources within the laboratory was necessary.

In order to minimize vibrational effects on the fluorescence signal, the laser employed for the fluorescence observations was placed on a granite slab, mounted on four small inner tubes. With a GR vibration meter, it has been observed that an improvement of approximately 16 dB is obtained in the noise level relative to the level when mounted on a laboratory table. Provision was made for mounting the modulation chopper above the granite slab with no contact with the slab.

The observations were significantly improved by replacing the InSb detector and external filter with a detector with a filter built into the dewar. The detector with filter in the dewar is a Judson Photovoltaic Indium Antimonide Detector with a detectivity

$$D^*(4.3,\ 900,\ 1) = 1.0 \times 10^{11}\ \frac{\text{cm Hz}^{1/2}}{\text{watt}} \quad .$$

The dewar of this new detector, in addition, provides greater electrical shielding than the dewar of the previously used detector. In the operation of the photovoltaic InSb detectors, it is important to operate with zero volts on the detector output.

With the new detector, noise level is much lower than with the previously employed detector. The laser is operated on single line transitions, determined to be the P(20), P(18) or P(16) in the cases considered. For single line, single mode operation of the CO_2 laser, the power output was low, usually below 200 milliwatts. Mode structure was observed with an Optical Engineering 10.6 μm Display Plate and by scanning a HgCdTe detector across the beam profile. Spectroscopic observations have shown that single line, single mode operation is achieved with a pair of apertures of 5 mm diameter within the laser resonator or with one adjustable aperture placed within the resonator. The Fresnel number for a 5 mm diameter aperture in this laser is approximately 1.1 so that the single pass diffraction loss for TEM_{10} is approximately 7% compared to approximately 0.6% for the fundamental TEM_{00} mode. On some occasions when the laser is tuned by the PZ drive, some overlap of the wings of lines is observable, but it was found that this did not hinder observation of the Lamb dip.

Observations performed with an external fluorescence cell included both FM and AM modulation of the laser output. Modulation rates between 200 Hz and 520 Hz were used. The FM output was achieved by placing modulation on the PZ element driving the rear mirror. The AM signal resulted from chopping the laser beam. The fluorescence traces show that the output signal was riding on a 4.3 μm background which comes directly from the laser. This has been observed by putting the laser signal directly into the InSb detector. No signal originating from the 10.6 μm laser output is observed in this manner because of the narrowband characteristics of the detector and filter. The loss of the derivative or chopped signal is further observed by replacing the CO_2 in the external cell with air. The 4.3 μm background signal is not observed in the derivative display when FM is applied to the laser PZ element. In turn, aperturing and defocusing of the laser output minimizes the 4.3 μm background.

With the internal control cell, the Lamb dip was observed with considerable strength. The observations, initially performed, were for pressures of 100 millitorr and 75 millitorr with the measurements at 75 millitorr providing the better signals.

The signals obtained with the internal cell are shown in the accompanying figures. Figure 1(a) shows the derivative of the Lamb dip for a CO_2 pressure of 75 millitorr. This trace was taken on the 10 μV sensitivity range of the PAR lock-in amplifier for a 300 millisecond time constant. With the sensitivity increased to the 2 μV scale and a time constant of 1 second, Figure 1(b) is obtained. Approximately 75 mW of 10.6 μm power was employed. The peak-to-peak voltage on the PZ corresponds to 15 volts. We have checked the voltage sensitivity of the piezoelectric elements since these initial observations by determining the half wavelength displacement with the Jarrell Ash spectrometer and by using a Michelson interferometer with a mirror on the PZ as one arm of the interferometer. The voltage sensitivity of the Jodon PZ used in the laser is approximately 0.23 μm/100V so that the frequency width of the derivative peaks is about 1.72 MHz. A wide variation in sensitivities of the PZ elements was observed in these measurements. Because of the large modulation width employed, the baseline

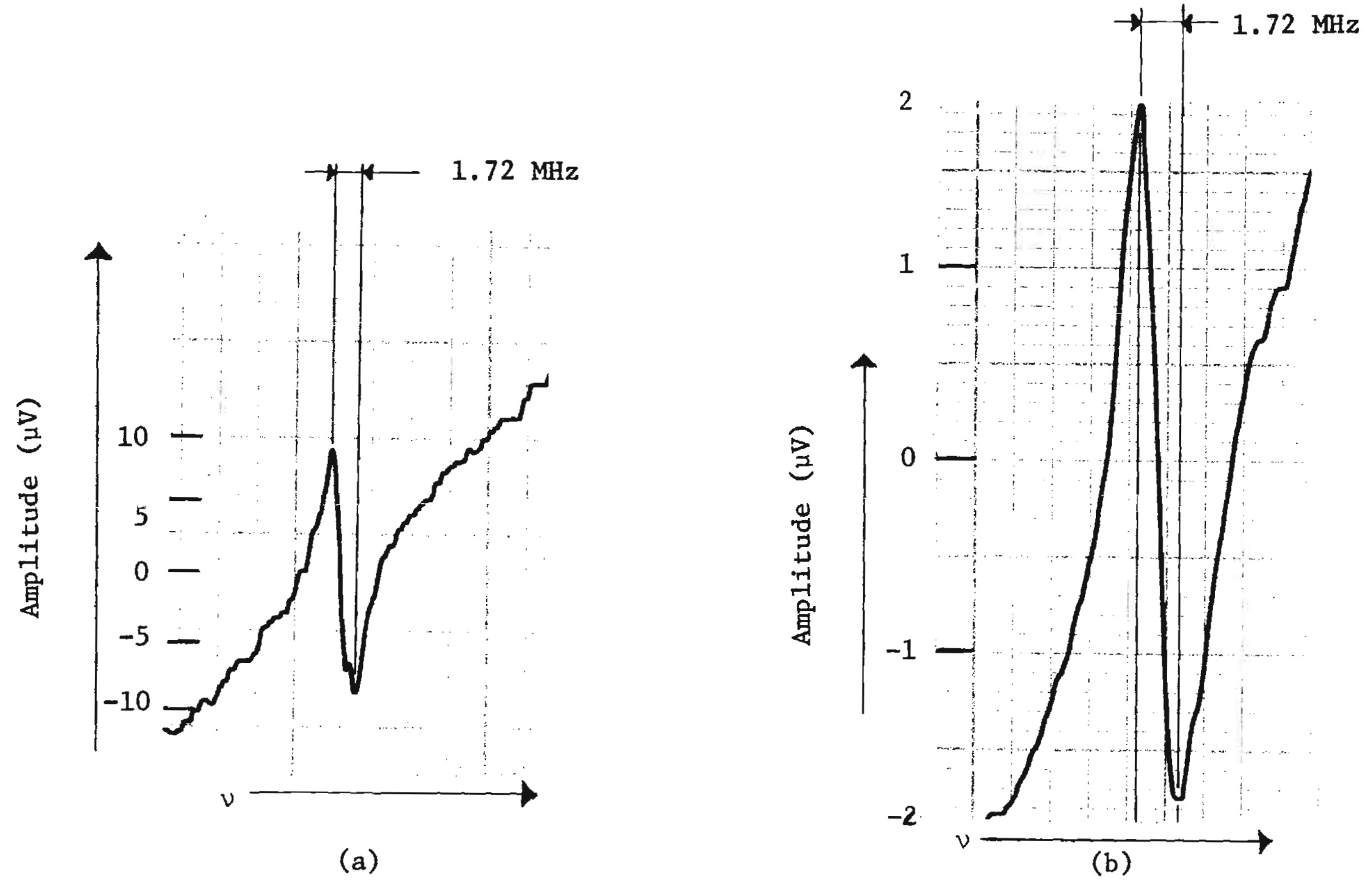


Figure 1. Traces of Lamb Dip of 4.3 μm CO_2 Fluorescence with Internal Cell for CO_2 Pressure of 75 Millitorr; Laser Power = 75 mW.

(a) 10 μV range of PAR Lock-in Amplifier; Time Constant = 300 ms.

(b) 2 μV range of PAR Lock-in Amplifier; Time Constant = 1s.

is not horizontal as a result of the Lamb dip derivative being superimposed on the derivative of the fluorescence. This is a broader line than that observed by Freed. As Freed has indicated, below 100 millitorr the linewidth is mainly determined by power broadening and by the molecular transit time across the diameter of the incident beam. Power broadening was shown to be occurring in these observations.

The aperture in the laser was opened to determine the limit to which one could increase the aperture and still maintain the Lamb dip. Figures 2 and 3 show the effects. The power was increased to 150 mW for Figure 2 and 200 mW for Figure 3. In Figure 2, the time constant was 1 second and the peak-to-peak amplitude of the Lamb dip derivative was 3.3 μV. In turn, the linewidth was increased by a factor of 1.5 over its value when excited by 75 mW, so that the width of the Lamb dip derivative was on the order of 2.6 MHz. It was assumed that the PZ sensitivity did not change during the time of measurements. For Figure 3, the time constant was 300 milliseconds, the peak-to-peak amplitude of the derivative 5 μV and the frequency width approximately 3.1 MHz. For these observations, the reflectivity of the output mirror was 95%, the modulation was 30 volts at 520 Hz, the lock-in time constant was either 1 second or 300 milliseconds.

In addition, the internal cell was employed with the laser power output reduced to 3 milliwatts corresponding to approximately 50 milliwatts inside the laser resonator. The Lamb dip linewidth (total half-power) was reduced to less than 0.8 MHz for a pressure on the order of 100 millitorr. This figure is compatible with Freed's measurements. No further changes in linewidth were evident as the power was reduced.

In the case of the external control cell, careful optical alignment was necessary to provide a standing wave with the laser signal. The cell is shown in Figure 4 with the InSb detector mounted on top of the cell. The cell, with a sodium chloride entrance window, is machined from a block of invar and gold plated internally. A gold mirror at the rear of the cell is aligned by three adjustment screws and the three axis movement to provide the single pass standing wave. A sapphire window on the top of the cell serves as a viewing port for the 4.3 μm radiation.

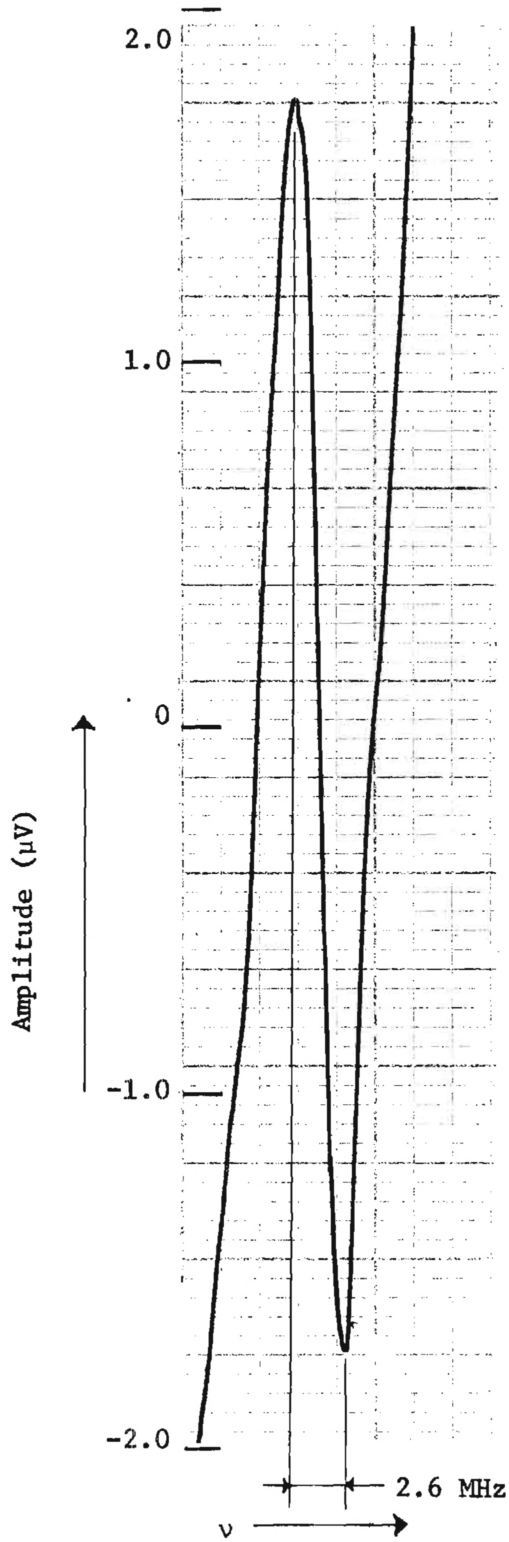


Figure 2. Trace of Lamb Dip of 4.3 μm CO_2 Fluorescence with Internal Cell Under Increased Laser Power, 150 mW. Time Constant = 1 sec.

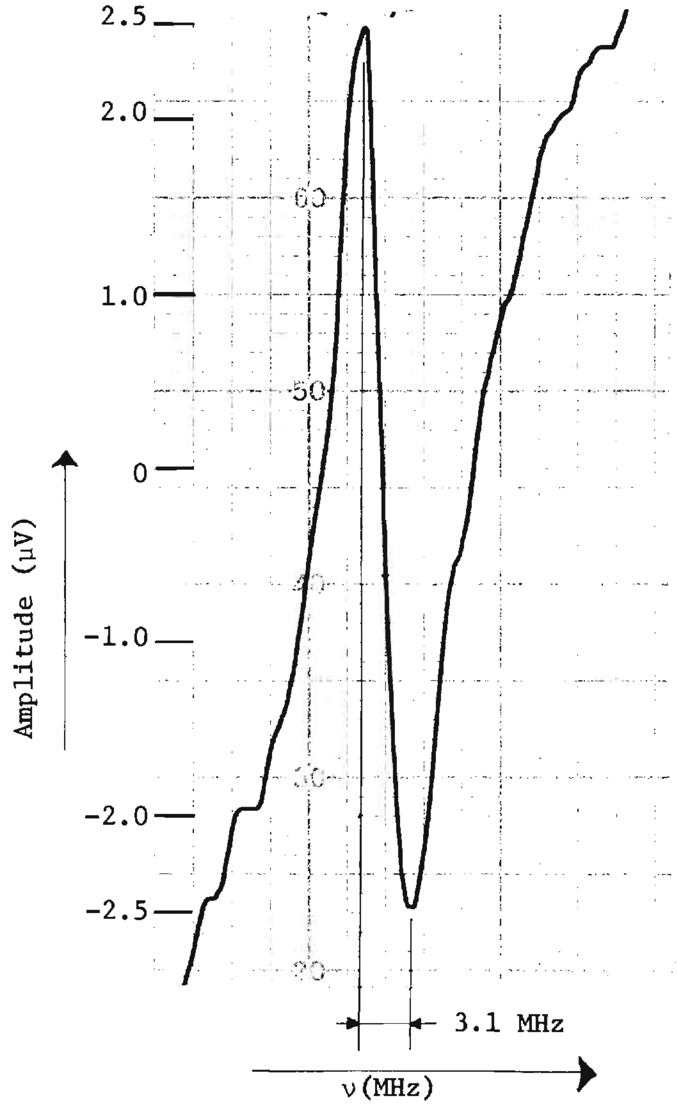


Figure 3. Traces of Lamb Dip of 4.3 μm CO_2 Fluorescence with Internal Cell Under Increased Laser Power, Approximately 200 mW. Time Constant = 300 ms.

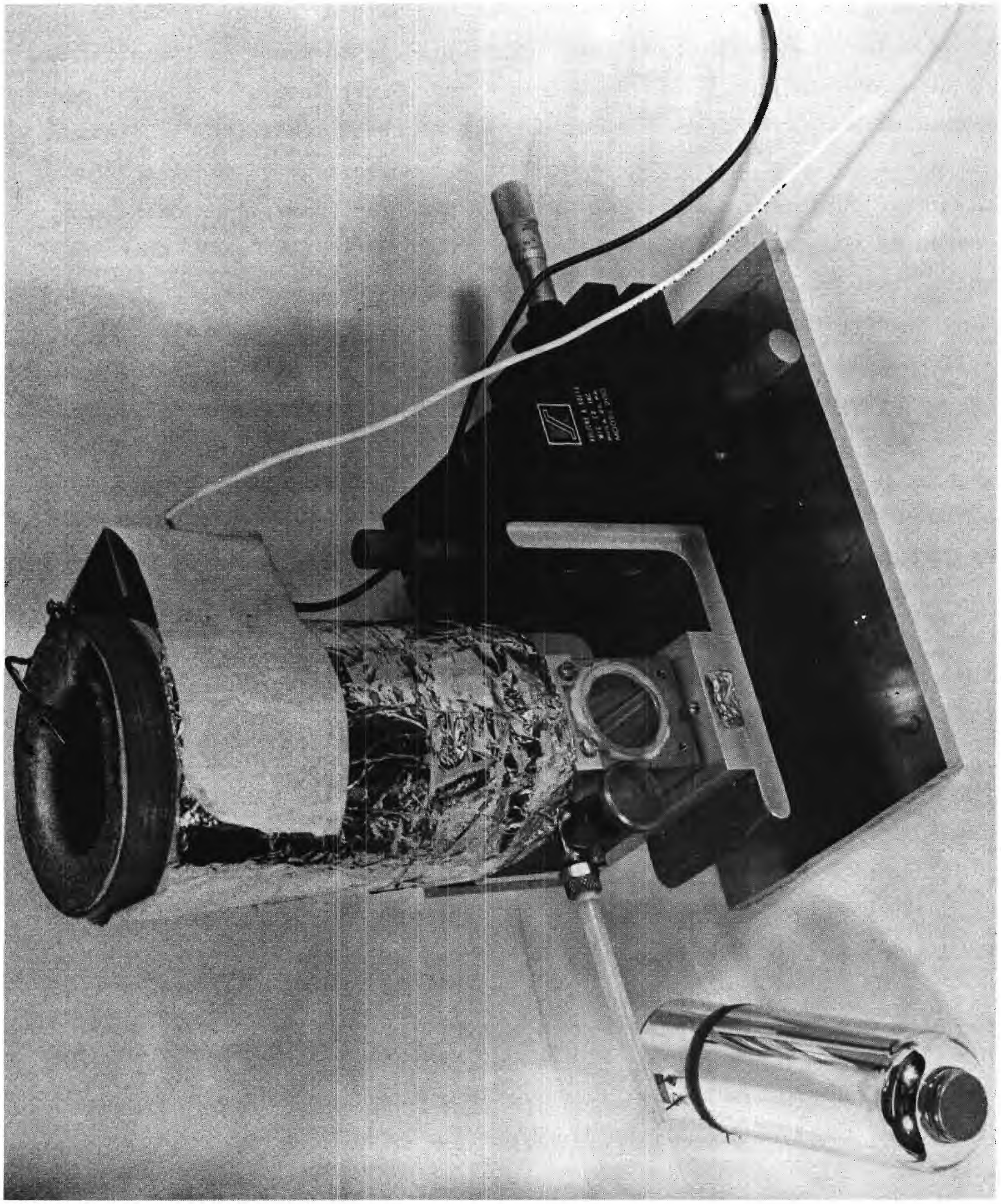


Figure 4. External Fluorescence Control Cell with 4.3 μm InSb Detector.

Initially, weak Lamb dips were observed with a chopper at 520 Hz between the fluorescence cell and the laser. Improvement in the alignment of the cell resulted in improved Lamb dips. Power levels of 90, 140 and 220 mW were used. Figure 5 shows a trace of three lines [P(16), P(18), P(20)] taken by scanning the laser with a ramp voltage on the laser Pz element. The laser power output was 140 mW. The three lines occur for a scan of 1000 volts on the PZ element. Notice, in this case, that the three lines are not fully resolved. For lower power levels, the transition on the left, the P(16) in Figure 5, did not exhibit the Lamb dip. The observations have been made for 100 millitorr and 80 millitorr of CO_2 in the fluorescence cell. Saturation broadening is observed at the high power levels, and only below 90 mW input power does the Lamb dip width show no power broadening. Expanding of the laser beam to fill the entire cell, except for the high power level (220 mW), resulted in loss of the Lamb dip. Figure 6 shows a derivative of the Lamb dip observed with the external cell. The excitation power in this case was 60 mW. The time constant for the lock-in amplifier was one second. The amplitude of the derivative was 3.4 μV peak-to-peak. With the CO_2 pressure in the control cell at 80 millitorr, the observed width of the derivative was 0.88 MHz.

The information obtained from these measurements indicates the critical nature of the alignment of the external cell to provide a standing wave, the power limitations particularly when the beam is expanded to fill the fluorescence cell, and the requirements on high detector sensitivity. All these factors are important for applications of the technique to a low power unit for use in the field.

3. Small CO_2 Lasers

The requirements on the CO_2 laser in a miniature molecular frequency are severe. Not only must the laser operate on a low power input, it must be a small uncooled sealed-off laser oscillating on single mode, single line. Initially, ULE structures were investigated for low power inputs. Despite the low power operation, heat dissipation problems were experienced. Other units which have been investigated have been discussed in the Second Interim Report.

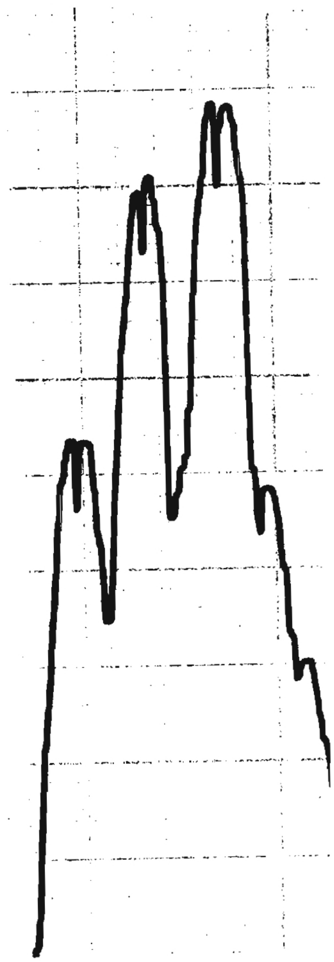


Figure 5. Trace of Three CO_2 Fluorescence Lines From External Control Cell.

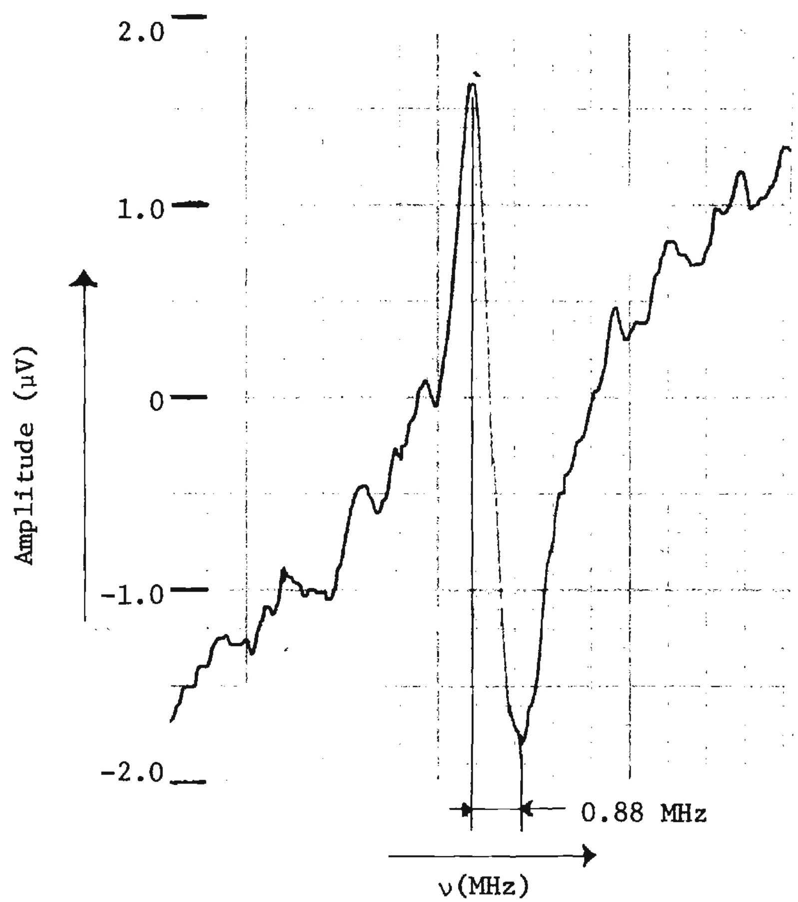


Figure 6. Derivatives of Lamb Dip in CO_2 Fluorescence from External Cell With CO_2 at 80 Millitorr, 1 Second Time Constant. The Excitation Power was 60 mW.

During the cours e of the program, three structures were successfully operated as lasers. A desirable configuration for the small laser devices would have a window internal to the laser so that the piezoelectric element would not be required to operate under vacuum conditions. For the small lasers in which the gain is low, it has been found that a window within the resonator has always prevented laser activity. Good reflectivity on the total reflectors and high reflectivity on the output mirror have been other requirements of the small units.

One of the small structures which has operated is a small water-cooled glass tube laser, six inches in length, capable of approximately 1.5 watts multi-mode output for 15-20 watts input (10 ma at 2 kV) corresponding to an efficiency of 7.5 - 10%. This represents a highly efficient source for a short laser, however, this value decreases significantly for single mode operation. It has, in turn, lased at 250 mW for input power on the order of 3 watts (8.3% efficiency). Smaller input power does not result in an observable laser output. The laser operates with a Max-R total back reflector and a 98% output mirror with no internal windows. The Max-R reflector has a reflectivity of 99.4 ± 0.2% at 10.6 μm. This small water-cooled laser can be sealed off, and lasing action is maintained. The bore diameter of the laser tube is approximately 8 millimeters. A smaller bore (3.7 mm) version of this tube has also operated but in single mode. The power consumption of this small bore tube is high, on the order of 15-20 watts, with an output power of 250 milliwatts corresponding to an efficiency of 1.25% to 1.6%.

In addition to these small glass tube units, a small laser, six inches long including the piezoelectric tuner, has been constructed from alumina tubing. This setup is shown in Figure 7. While the alumina tube has dissipated sufficient heat to permit laser action, beryllium oxide is a more desirable material as shown in Table 1, which gives the thermal conductivity of comparable materials. It is seen that the thermal conductivity of BeO is twice that of aluminum and over twelve times that of alumina. For this alumina tube configuration, an output of approximately 1 watt was obtained. The bore of the tube is 8 mm so that the output is

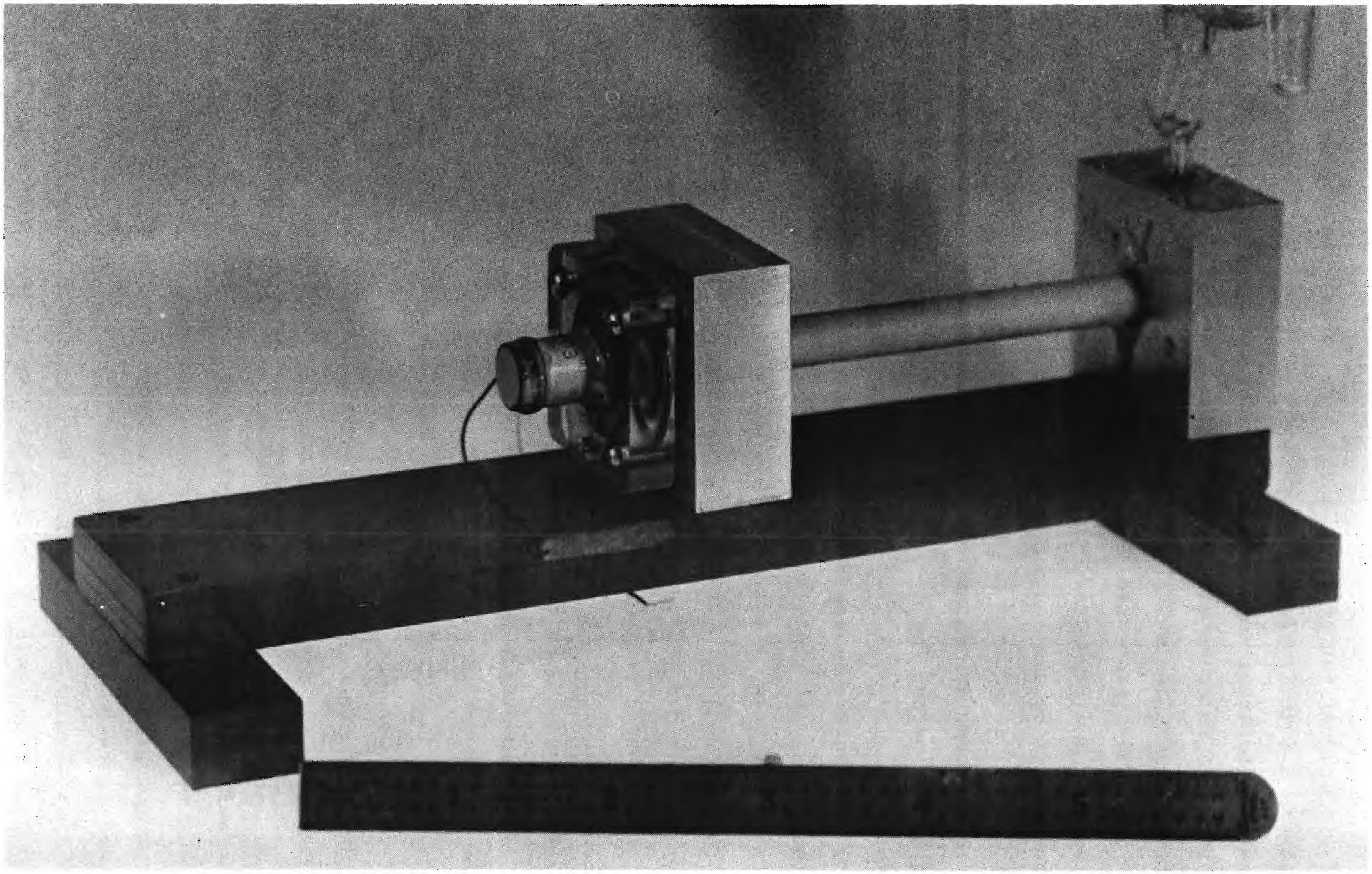


Figure 7. Room Temperature CO_2 Laser with Alumina Tube.

Table 1

Thermal Conductivity

Material	T(°F)	(BTU/HR·FT·°F)
Pyrex	100	0.68
Alumina	100	11.0
Aluminum	100	64.0
Beryllium Oxide	100	130.0

multi-mode. The input power was 12.5 watts (5 ma at 2.5 kV). Thus far, it has not been possible to operate this room temperature laser in a sealed-off mode, quite probably due to the heat dissipation problems. The substitution of BeO tubes for the alumina and provision of heat sinking are expected to correct this situation. The output power of 1 watt for 12.5 watts input again represents a high efficiency of 8%.

An additional unit which has resulted in laser action is one of the small invar blocks which were described in the Second Interim Report and shown in Figure 4 of that report. This is one of the smallest CO_2 lasers which have thus far been operated. The operational unit has been modified from the apparatus which was originally shown. The internal Brewster angle window has been removed. The invar block is approximately 3-3/8" long; the total length including the piezoelectric element and mirrors is approximately 4-1/4 inches. The ballast tank has been removed, although this is a desirable feature to include. The invar block was grounded, and the high voltage was applied through a quartz spacer on one end of the block and insulated internally from the block by extending the BeO tubes through the block. Initially, operation with a copper electrode at the center of the tube was investigated; however, breakdown of both sides of the discharge for the small structures was difficult. The center electrode piece, instead, served only as the gas inlet to the system. Figure 8 shows the invar unit.

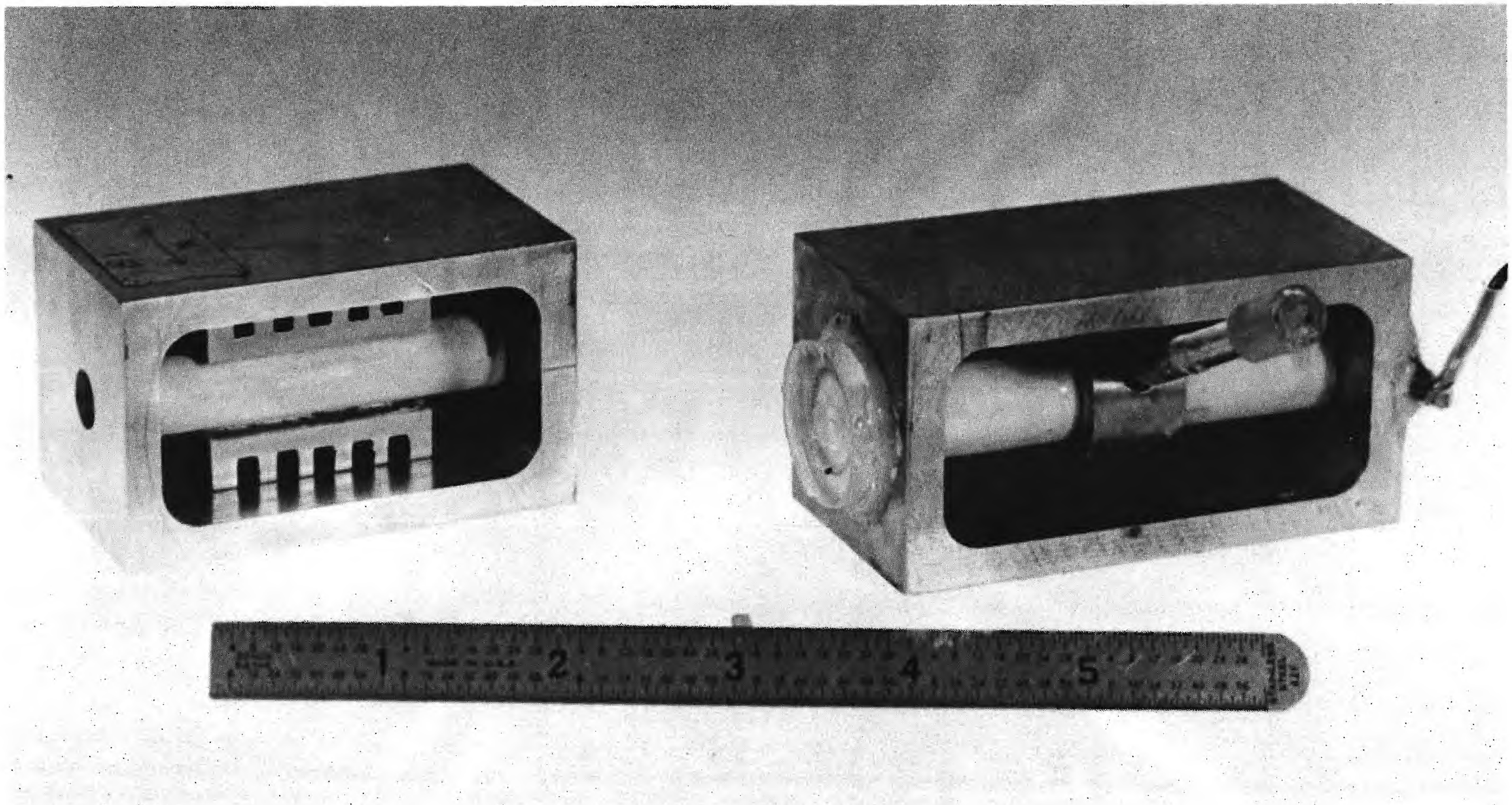


Figure 8. Invar Blocks with BeO Tubing for Small Room Temperature CO_2 Laser.

The tubing in the invar block is BeO with a 6 mm bore. The laser produces approximately 1/4 watt multi-mode at 7.5 watts input (5 ma at 1.5 kV). The invar frame provides a stable resonator configuration. Thus far, it has not been possible to continue to lase with the system sealed off. Improvements in heat dissipation, vacuum sealing materials and techniques and lower power consumption are necessary. These units look promising if single-mode operation at good output power can be obtained with the above improvements. For this short multi-mode laser, the total gain has dropped considerably so that the efficiency of the unit is now on the order of only 3%.

4. External Modulation

For a stable molecular frequency source, it is important to avoid the application of frequency modulation to the laser resonator. It is, therefore, desirable to employ an external modulator. This is possible when an external control cell is used. Several techniques exist for doing this, but limitations imposed by the CO_2 molecular system and the requirement of a miniature, low power modulator have caused difficulties in obtaining an appropriate unit.

An external electro-optic phase modulator was investigated in the First Internal Technical Report. In Appendix II of that report, it was shown that for the conventional 10.6 μm modulator, the low frequency modulation rates imposed by the long lifetime of the upper state of the 4.3 μm fluorescence results in the power requirements, for generating the necessary modulation voltages, being impractical for our small devices.

Several versions of the Doppler dither technique have been investigated. This method has been employed by several investigators in large devices which required greater driving power than available in the miniature laser system [2]. The following small modulation units have been considered:

(1) Stacked piezoelectric elements could be employed but these would exceed the space which can be allotted for the modulator. In a system employing two reflections from a moving mirror mounted on

a stack of PZ elements, the total maximum frequency deviation is given by $\Delta\nu = \frac{16\pi A f}{\lambda}$ where A is the amplitude of the vibration, f is the modulation frequency, and λ is the laser wavelength. For $\Delta\nu \approx 0.12$ MHz, f = 500 Hz, and λ = 10.6 μm, the required amplitude of vibration is A = 0.118 mm so that the total movement of the mirror is 0.236 mm. This displacement will provide a frequency deviation on the order of 1/6 of the derivative width so that the phase-sensitive output is a reasonably accurate plot of the first derivative of the line shape. To obtain such a displacement, a stack of 60-70 piezoelectric elements with a driving sinusoidal voltage on the order of 1000 volts is required. This is an impractical arrangement for a small modulator scheme. Other investigators have employed mirrors driven by solenoids, but the power consumption and size are unfavorable for our use.

(2) Detailed consideration was given to the use of miniature speakers as the moving elements for Doppler dither systems. One small element with the cone cut away was shown to produce mirror translations in excess of a millimeter, but considerable "wobble" of the mirror was present during the motion. The "wobble" persisted down to displacements which were a small fraction of a millimeter. The motions of the mirror were studied by using the moving element as one of the mirrors in a Michelson interferometer employing an argon laser. A resonance in the motion existed at approximately 150 Hz. Relatively small power consumption, approximately 72 milliwatts, was required for this motion. Further power reduction was possible when the speaker coil was resonated, but this condition makes the system susceptible to external vibration. A modulator employing a moving mirror mounted on a speaker element and held aligned with telescopic tubing was constructed and shown to have greater stability than previous configurations. Other small devices, such as earphone speakers, piezoelectric bimorphs and sonic transducers were investigated but none of these small devices were shown to have sufficient stability and small power consumption for use in our system.

(3) Investigations were performed on the use of a rotating mirror in conjunction with a stepped mirror to produce a path length change. This technique has been briefly described in the Second Interim Report. Initially a torsional piezoelectric element was considered as the means of rotating the mirror. Insufficient displacement is obtained with any element of practical size. A review of the literature indicated that at least two scanners are available which can meet our power requirements and also be compatible with the size requirements. One optical scanner, a taut band type, made by American Time Products, has the disadvantage of being a mechanically resonant device and is probably susceptible to vibration in our application.

The other scanner is one of a series of devices made by General Scanning. The Model G-124 has characteristics which meet several of our requirements. This particular scanner has a sensitivity of 50 mA/degree, is relatively small and is sufficiently stable to be used in a modulator. The units have wobble typically below 10 arc-seconds and have a frequency range from dc to approximately 980 Hz. The voltage required to produce a given drive current is

$$E = iR + L\frac{di}{dt} + B\dot{\theta}$$

where R = resistance of the coil (8 ohms), L = coil inductance (4 mH) and B = the back-emf constant (0.23 mV/degree/second). For approximately 1.5 degrees deflection, 0.729 volts is required with a power consumption of 0.055 watts.

One of these scanners has been tested for performance. With a helium-neon laser, the power consumption for peak-to-peak deflection was checked for several frequencies. At 400 Hz, for a power consumption of 0.096 watts, a deflection of 4.1° was obtained while for 0.050 watts, the deflection was 2.3°.

A unit, similar to Figure 7 of the Second Interim Report, was assembled with the scanner and a stepped mirror. A helium neon laser was used to trace the path of the beam. At the position which would be occupied by the control cell, undesirable lateral displacement of the beam was observed. For this technique to work successfully, detailed consideration must be given to the correct shaping of the stepped mirror to achieve a good superposition of the two signals reflected from the stepped mirror. Because of the time consumed in developing this technique, it was decided to work toward a workable system using internal modulation on the PZ element of the laser resonator. While no satisfactory external modulator has been developed as yet for the miniature laser, it is important that such a unit be developed. Mechanical stability and high power consumption are the major deterrents which must be overcome.

5. Fluorescence Detector Array

One of the most difficult aspects of the miniature molecular frequency source is the requirement of using room temperature detectors. In the First Interim Technical Report, calculations were presented to show the feasibility of employing an array of room temperature detectors lining the walls of the fluorescence control cell. These calculations are presented with modifications in Appendix I. Figure 6 of the Second Interim Report shows the array configuration which would line one side of the control cell. Thus, twenty detector elements in each cell would be used to detect the 4.3 μm fluorescence radiation. Several detector materials were considered for room temperature operation. The pyroelectric detector, it was concluded, is not sensitive enough for the room temperature observations. Detector manufacturers have recommended the use of a single thermoelectrically cooled PbSe detector on each side as being superior to the room temperature arrays; however, the power consumption for the thermoelectric elements far exceeds the power allowed for operation of the system.

Several alternates to the 20 detector array were studied. One such scheme would employ reflective surfaces on two sides of the control cell so that only 10 detectors, five on each of the remaining two sides, would be necessary. In order to minimize the number of detectors, optimum collection optics were investigated in the form of such devices as an integrating sphere with a single detector.

The most sensitive detector material for room temperature operation is lead selenide, PbSe. Twelve detector arrays of five detectors each were purchased from Optoelectronics for use in three miniature molecular frequency sources. The detectors are mounted on quartz substrates, and the arrangement for their use is such that the arrays are located inside the control cells on each of the four side walls. The detectors have a transmitting dielectric coating over them so that they can be employed in the vacuum without being affected by the CO_2 vapor. No narrowband filter is used with these detectors. The control cells are rectangular aluminum tubes, approximately 3 inches long with an internal cross section of 1 inch by 1 inch. The cell is a single pass cell with a mirror at the rear and a sodium chloride entrance window. Figure 9 shows one of these cells. The data sheet for the 12 PbSe detector arrays is given as Table 2. The detectivity $D^*(\lambda_{pk}, 1000, 1)$ of the array units ranges from 0.86 to 2.79 x 10^9 cm $Hz^{1/2}$ W^{-1}. These detectivities are calculated from the test conditions listed on the data sheets. Thus, D^*, the detectivity normalized to unit area and unit bandwidth is a measure of the signal-to-noise ratio and is given by

$$D^* = \frac{V_s}{V_n} \frac{\left[\frac{\Delta f}{A}\right]^{1/2}}{H}$$

where V_s = signal voltage developed across the detector terminals (rms volts),

V_n = noise voltage developed across detector terminals (rms volts),

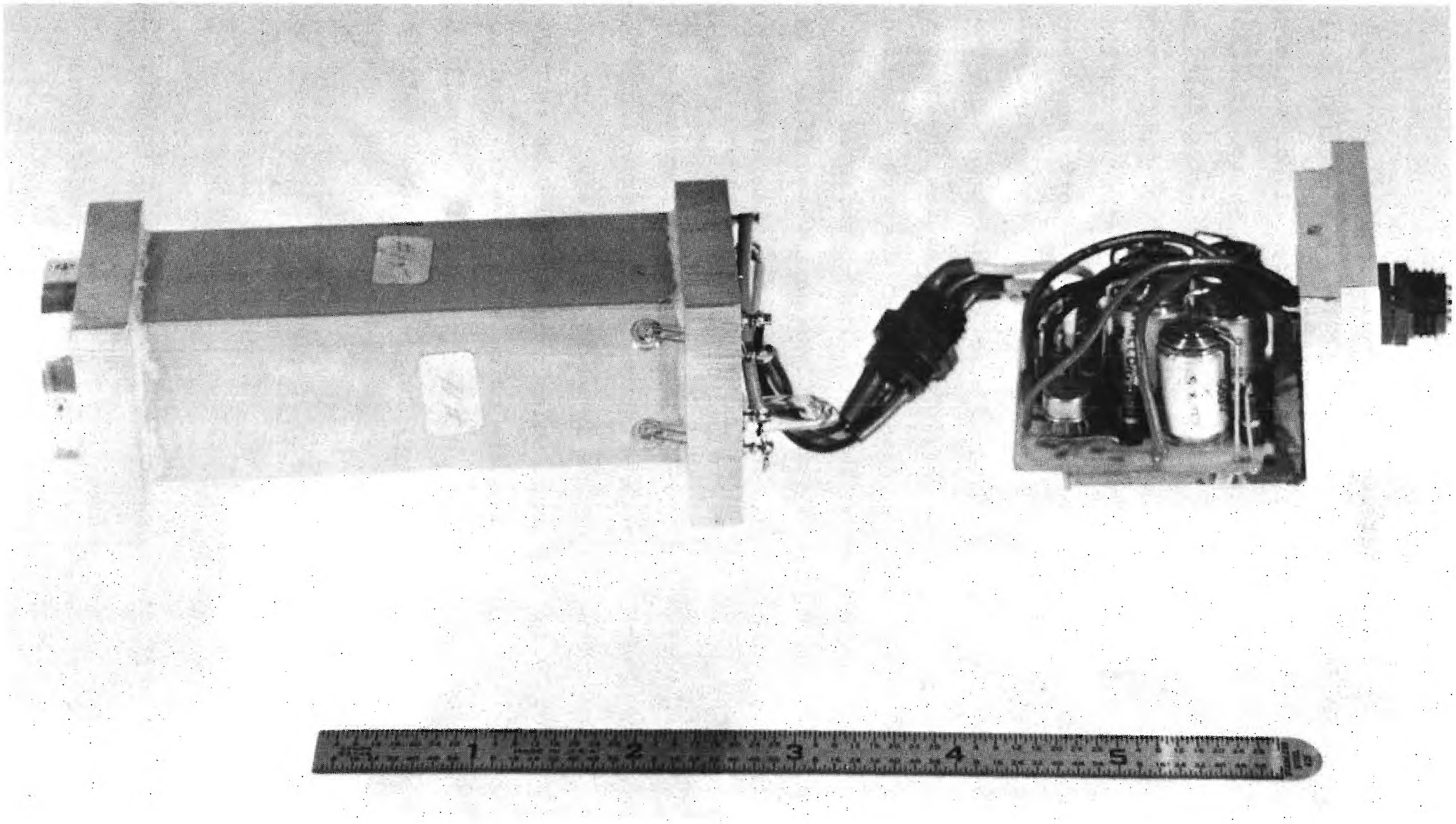


Figure 9. External 4.3 μm Fluorescence Control Cell with Room Temperature PbSe Detector Arrays.

TABLE 2

OPTOELECTRONICS, INC.

1300 Dynamic Street - Petaluma, Ca. 94952

DATA SHEET

PROJECT NO. PPI- 1852

DETECTOR MATERIAL PbSe

PART NUMBER OE-10 X

TESTED BY E.P.

DATE May 20, 1974

Q.A. ACCEPT QC-1 5-21-74

ELEMENT SERIAL NUMBER	THERMOELECTRIC COOLER		THERMISTOR RESISTANCE		DETECTOR DARK RESISTANCE		DETECTOR BIAS (VOLTS)	SIGNAL (μVOLTS)	NOISE (μVOLTS)	SIGNAL TO NOISE RATIO	RESPONSIVITY (λpk, 1000) (VOLTS/WATT)	D* (λpk, 1000) (CM Hz $^{1/2}$ W $^{-1}$)
	VOLTS	AMPS	AMBIENT (KΩ)	COLD (KΩ)	AMBIENT (MΩ)	COLD (MΩ)						
1					.081		500	195	0.55	355	84.5	1.35×10^9
2					.094		500	195	0.45	433	84.5	1.65×10^9
3					.060		500	180	0.35	514	78.0	1.96×10^9
4					.103		500	225	1.00	225	97.5	0.86×10^9
6					.150		500	340	0.85	400	147	1.52×10^9
7					.146		500	370	1.30	285	160	1.09×10^9
8					.055		500	120	0.35	343	52.0	1.31×10^9
10					.121		500	330	0.45	733	143	2.79×10^9
11					.086		500	265	0.75	353	115	1.35×10^9
12					.057		500	125	0.25	500	54.2	1.91×10^9

TEST CONDITIONS

BLACKBODY TEMPERATURE 500 Degrees Kelvin

FLUX DENSITY 2.98×10^{-6} Watts/CM²

CHOPPING FREQUENCY 1000 Hertz

NOISE BANDPASS 10 Hertz

OPERATING TEMPERATURE 298 Degrees Kelvin

HEAT SINK TEMPERATURE N/A Degrees Kelvin

DETECTOR ELEMENT SIZE 1.27 X 6.1 CM

AREA 7.74 CM²

[illegible] 10

APPROVAL [illegible]

TEST SCHEMATIC

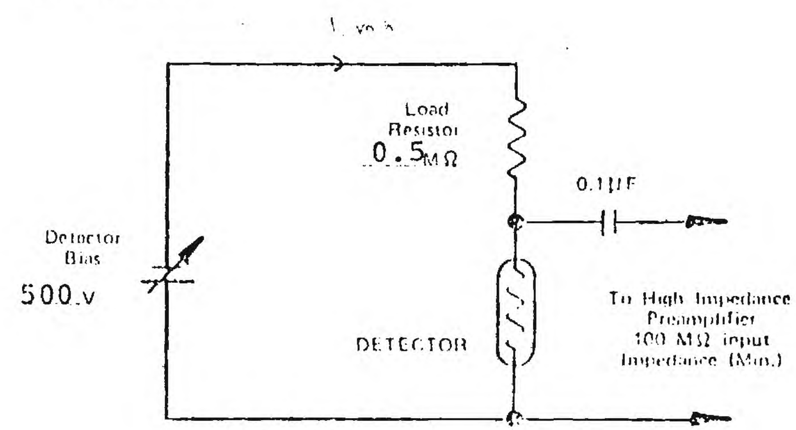


TABLE 2 (Concluded)

OPTOELECTRONICS, INC.
1309 Dynamic Street · Petaluma, Ca. 94952

DATA SHEET

PROJECT NO. PPI- 1852
DETECTOR MATERIAL PbSe
PART NUMBER OE-10X
TESTED BY E.P.

DATE May 20, 1974
Q.A. 5-21-74
PG. 2 OF 2

ELEMENT SERIAL NUMBER	THERMOELECTRIC COOLER @		THERMISTOR RESISTANCE		DETECTOR DARK RESISTANCE		DETECTOR BIAS (VOLTS)	SIGNAL (μVOLTS)	NOISE (μVOLTS)	SIGNAL TO NOISE RATIO	RESPONSIVITY (λpk, 1000) (VOLTS/WATT)	D* (λpk, 1000, 1) (CM Hz 1/2 W-1)
	VOLTS	AMPS	AMBIENT (KΩ)	COLD (KΩ)	AMBIENT (MΩ)	COLD (MΩ)						
13					.063		500	170	0.25	680	73.7	2.60×10^9
15					.079		500	180	0.40	450	78.0	1.72×10^9

Electrical Measurement of 5 Element Array was made with elements in parallel.

A = detector sensitive area (cm^2), and

H = radiant flux density incident on the detector sensitive area (rms watts per cm^2).

For the signal-to-noise ratios given in Table 2, the flux density of the 500°K black body = 2.98×10^{-6} watts/cm^2, a noise bandpass of 10 Hz and an area of 7.74 cm^2, the last column of Table 2, D^* (λ_{pk}, 1000, 1) is obtained by using the relationship

$$\frac{D^*(\lambda_{pk})}{D^*(BB)} = 10.$$

An inherent undesirable aspect of the use of large area room temperature detectors is the high detector bias voltage (500V) which is required for these units. The three control cell units were assembled with the detectors mounted internally on the side walls of the cell. The signals from the four detectors in each cell are added before being applied to the pre-amp and the lock-in amplifier. It has been possible to detect the 4.3 μm fluorescence with these control cells, but thus far no Lamb dip has been observed. The observations have been performed with control cell pressures on the order of 50-150 millitorr. The single mode laser power level was approximately 100-200 mW, which should be adequate for saturation of the resonance. The signal level of the fluorescence is 1-2 orders of magnitude less than the fluorescence signal strength observed with the cooled InSb detector. The alignment for the standing wave in the control cell is critical. On several occasions, the possibility of the presence of a Lamb dip was considered; however, the suspicious dip was not significantly distinguished from noise. In order to enhance the signal, a Fabri-Tek signal averager was employed, but again no features were distinguishable as the Lamb dip. While the Lamb dip has not been observed with these room temperature detectors, continued effort is necessary before a complete evaluation can be given.

6. Beam Expander/Collimator

In order for the 10.6 μm radiation to fill the control cell in the small laser system, a beam expander/collimator is employed. Off-axis parabolic reflectors were considered; however, a small inverse Galilean telescope arrangement appears to provide the most compact configuration. The expander/collimator is shown in Figure 10. The lenses for this arrangement are anti-reflection coated germanium meniscus lenses. The small negative lens has a focal length of 1/2 inch and is 1/2 inch in diameter. The larger positive lens has a focal length of 3 inches and is 1 inch in diameter. The lenses are mounted in a cylinder to yield a magnification of 6, so that a laser beam on the order of 2-3 mm diameter will fill the control cell, which has an ID on the order of 3/4 inch. The beam expander/collimator has been checked on the bench and shown to expand and collimate a CO_2 laser beam appropriately. The unit is used directly in front of the window of the control cell.

7. Isolator

In order to avoid reflected signals entering the CO_2 laser which can result in undesired pulling of the laser, an isolator is required between the control cell and the laser. The most appropriate isolator consists of a Brewster angle polarizer and a quarter-wave plate. Originally it was planned to use a Brewster angle window in the miniature CO_2 laser; however, losses from a window being placed in the laser resonator prevented lasing action. As a result, the isolator consists of a Brewster angle beam splitter in conjunction with the quarter-wave plate.

The beam splitter serves to polarize the beam passing through to the control cell and to provide a laser source output useable as an external stabilized signal. The beam splitter which is employed is a zinc selenide plate set at the Brewster angle. The quarter wave plate is a cadmium sulfide plate from Cleveland Crystal. The plate is a 1/2-inch square with AR-coating on both sides. The optic axis has been checked with a CO_2 laser and shown to lie parallel to one side of the quarter wave plate.

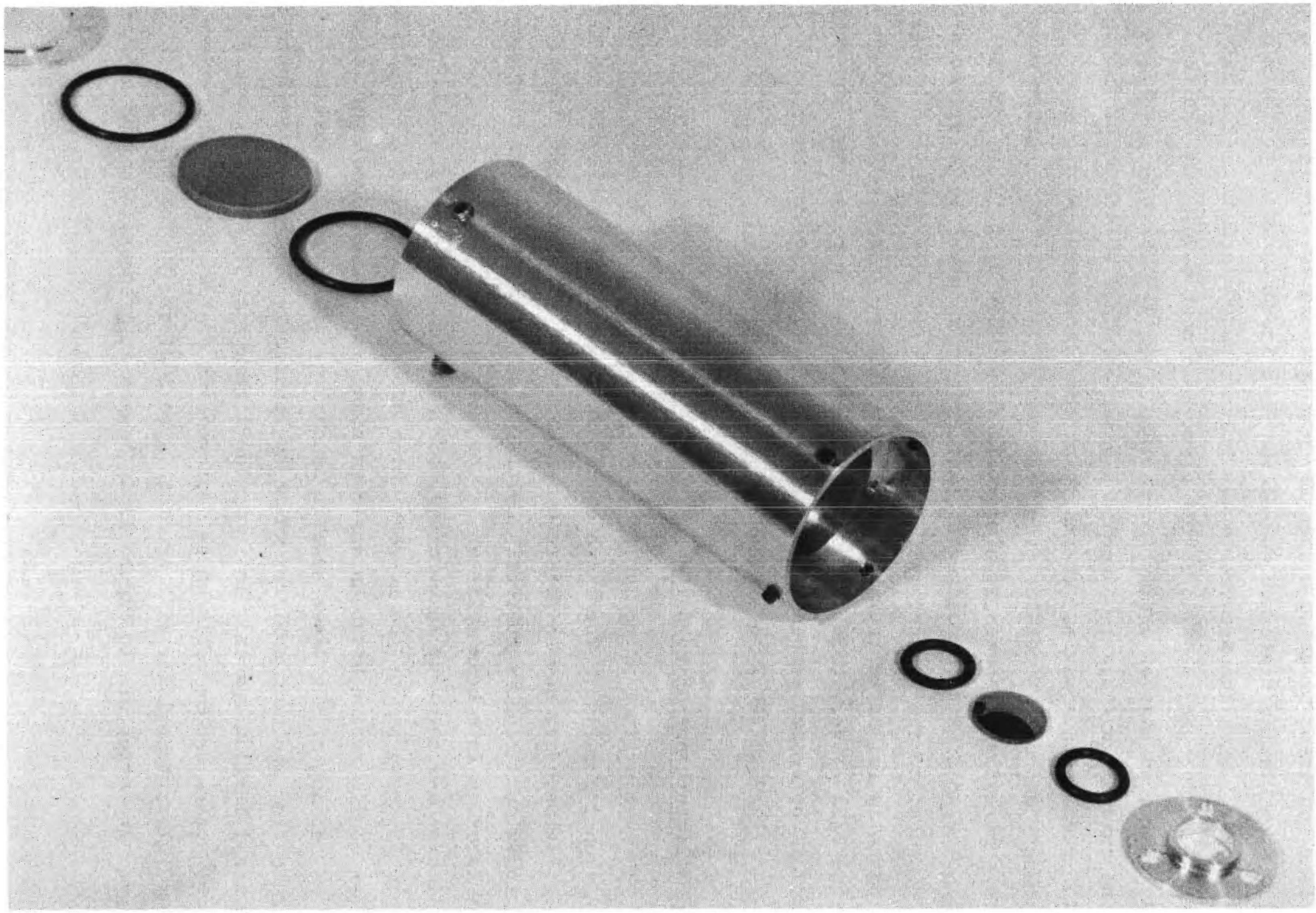


Figure 10. CO_2 Laser Beam Expander/Collimator.

The test consisted of using a linearly polarized laser, the Optical Engineering 10.6 μm Display Plate and one of the ZnSe Brewster angle polarizers as an analyzer. With the Brewster angle plate cross-polarized to the laser output, the spot on the fluorescent plate is almost completely extinct. It is estimated that an extinction ratio of 0.05 is achieved. Insertion of the quarter-wave plate between the laser and ZnSe polarizer at an angle of 45° results in a maximum intensity of the fluorescent spot.

When used as an isolator, the Brewster angle polarizer/quarter wave plate combination disposes of almost all return signal from the control cell. The polarizer is mounted so that the laser output is polarized along one diagonal of the quarter wave plate. The circularly polarized signal from the plate is reflected from the rear mirror of the control cell through the quarter wave plate. Upon striking the Brewster angle polarizer, the reflected signal is polarized perpendicular to the original direction and thus does not pass through the polarizer to the laser.

8. Miniature Assembled Units

Three miniature molecular frequency sources have been assembled in a linear configuration. The three units, upon completion, will allow heterodyning between any two to determine stability of the controlled lasers. The individual sources currently consist of a water-cooled six-inch glass tube laser, a ZnSe beam splitter, a CdS quarter wave plate, beam expander/collimator and the room temperature PbSe fluorescence control cell. Figure 11 shows one of the sources which have been assembled. The simple linear configuration has been employed since an internal modulator is used and no bending of the laser beam is necessary. The useful signal is extracted from the beam splitter while the transmitted signal is employed in the stabilization system. In turn, the arrangement is such that any element of the source can be replaced as improvements are developed. The water-cooled glass tube laser will eventually be replaced by the invar block laser. The structure in Figure 11 is housed in a square aluminum tube.

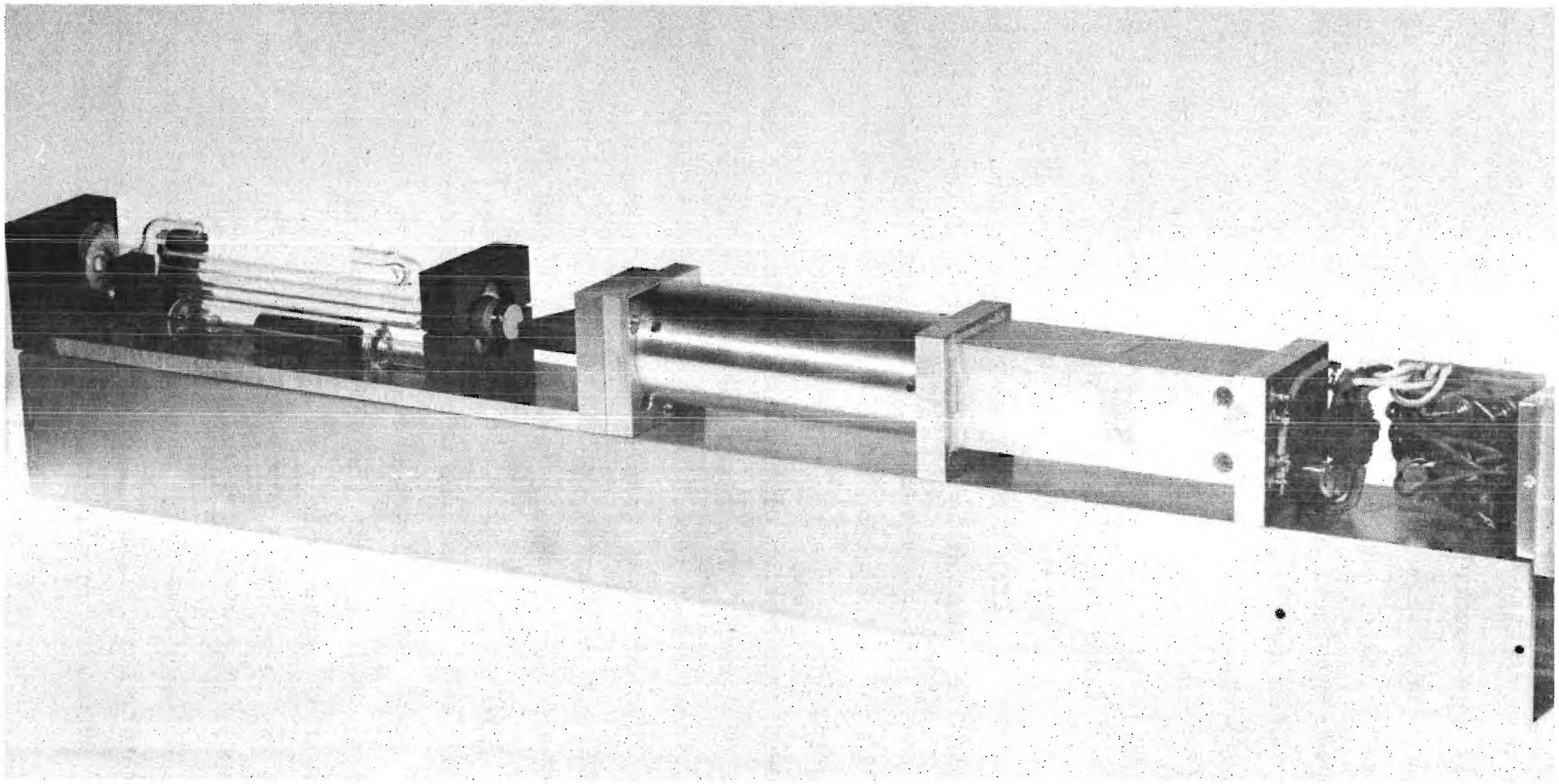


Figure 11. Miniature CO_2 Molecular Frequency Source.

Currently, the miniature source volume is larger than the design goal which we originally set out to meet. The volume of the device in Figure 11 is approximately 55 in^3 (or 64 in^3 including the pre-amp). This compares with the design goal of 20 in^3. The replacement of the water-cooled laser by one of the invar blocks will reduce the volume by 6 in^3. A more compact combination of the beam splitter and polarizer will result in further reduction from the 6 in^3 that they presently occupy. The inverse Galilean telescope occupies considerable space (12.25 in^3). The fluorescence control cell housing the room temperature PbSe detectors is large in volume (13.8 in^3) in order to provide sufficient molecules at low pressure ($\sim$50 millitorr) and large detector area for a strong enough signal to stabilize the CO_2 laser. It is estimated that with the invar laser, reduction of the size of the beam splitter-quarter wave plate assembly, possible elimination of the expander/collimator by proper shaping of the laser output mirror and reduction of the cross-section of the unit, the total volume can be reduced to 20 in^3. Inclusion of an external modulator would increase this volume slightly.

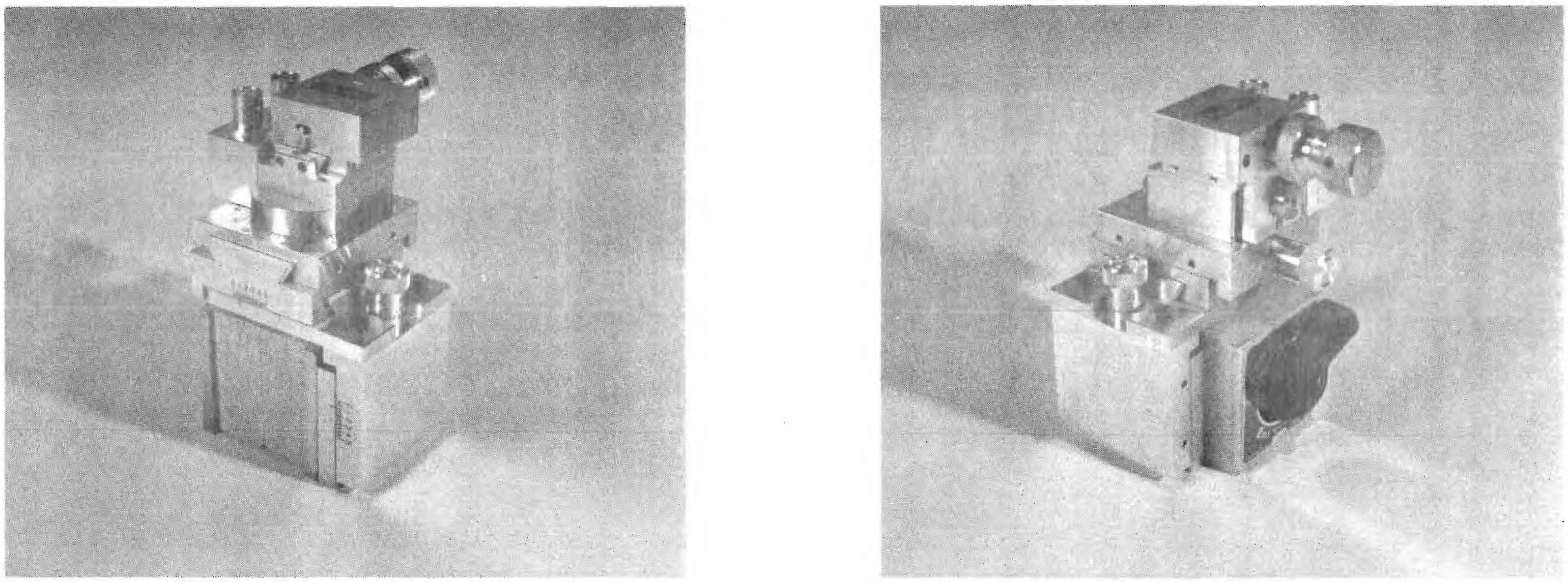
The power consumption of the unit in Figure 11 exceeds the design goal power level of 1 watt. The glass laser power consumption is $\sim$ 15 watts while that of the invar laser is 7.5 watts. The high bias voltage of the room temperature PbSe detectors results in the requirement of an input power of $\sim$ 0.500 watts for each array or 2 watts for each control cell. While the control cell has yet to show a Lamb dip, the goal of using room temperature detectors which was originally set at the start of the contract appears feasible and should be achieved with continued effort. Investigations using metal-oxide-metal diodes should be made in an effort to achieve room temperature operation. With the current power outputs of 250 mW at 3% efficiency, it is conceivable that single mode operation of 50 mW at an improved 5% can be achieved and that this will be sufficient power under optimized operation to cause saturation. The use of small waveguide lasers with bores in the 1-2 mm range should be investigated since the small bore waveguide lasers have higher gain and efficiency than a larger bore normal mode laser. However, in all cases in which waveguide lasers have been employed, none have operated at the low power levels required in our apparatus and high power dissipation has occurred in the use of small bores. In turn, stabilization methods employing the Lamb dip technique have not been investigated thus far for waveguide lasers, but both alumina and beryllia have been successfully used in room temperature versions.

In the case of the room temperature PbSe detectors, the bias voltage is high because of the size of the detector elements. Other configurations which would reduce the requirements on the bias voltage are possible, but the detector manufacturers were not prepared to provide configurations more complicated than the large elements which are mounted in the fluorescence cells. The room temperature PbSe detectors have been compared with the thermoelectrically cooled PbSe detectors. The cooled detectors require an input power of 2.0 watts for operation of the thermoelectric cooler. It has been recommended that two of these detectors on the walls of a control cell could be used.

9. Heterodyning Device

For the frequency comparison of molecular frequency sources, the heterodyning at 10.0 μm can be performed in different mixing devices. One of these is the HgTe, CdTe photovoltaic detector which is sensitive in the heterodyne mode but requires cooling to 77°K. Another unit is a metal-oxide-metal diode (MOM) which operates at room temperature and can be employed for heterodyning in the field.

Figure 12 shows a MOM diode mounted on a micropositioner and magnetic base. These units are constructed by Custom Microwaves. In Figure 12(a), the front view of the diode, the post at the top of the unit can be seen. The nickel post is driven, by a differential screw seen at the rear in Figure 12(b), into a one mil tungsten whisker. The diode can be rotated in the horizontal plane for optimization of the input of the two signals to the diode junction. One of these MOM diodes is currently available for heterodyning of the CO_2 laser source.



(a) (b)

Figure 12. Metal-Oxide-Metal (MOM) Diode for Heterodyning of CO_2 Laser Sources, (a) Front View; (b) Back View.

10. Recommendations and Conclusions

The program on miniature molecular frequency sources has been an initial investigation of several infrared devices and techniques applicable to the 10.6 μm region. As stated previously in this report, no aspect of the miniature source has proven infeasible, but detailed research must be performed on each component of the system in order to achieve a workable miniature device. It has been possible to identify problems associated with each critical element of the system. The most critical problems which must be solved are operation of a low power miniature CO_2 laser, development of a miniature external frequency modulator, availability of sensitive room temperature detectors and minimizing of the overall power consumption. Recommendations and conclusions can be made concerning each item in the molecular frequency source.

(a) Small CO_2 Laser

The CO_2 laser has been shown to operate in miniature form. In this program, laser action has been observed in units as small as 4-1/4 inches. The output is multimode. To be a useful source, the lasers will have to be operated single-mode. The invar frame can provide a stable resonator for the laser, but improved vacuum sealing of the units is necessary. Such techniques currently exist [3]. The alumina tube can be replaced by a beryllia tube of smaller bore to support a single mode. Improved heat sinking is necessary for air-cooling operation of the laser.

For heat sink purposes, the small BeO tubes can be gold plated to provide both the heat sink and electrode contacts. It should be kept in mind, however, that despite their good thermal conductivity properties, beryllia and alumina are poor resonator materials as their lengths vary drastically with temperature, so that the invar or ULE quartz resonator frame is necessary.

The ULE quartz parts which have been investigated are not suitable for CO_2 resonators even at low power without conductive bores inserted in them. The availability of diamond drills in the laboratory will provide the opportunity of preparing the quartz parts for use with BeO tubes. Again, heat sinking will be required to remove the heat from the BeO tubes.

The operation of these lasers in single mode will result in an estimated 50 milliwatts unless a larger laser is used. This power level presents problems in the use of room temperature detectors. The power consumption of the small lasers presents another critical area. Power input levels on the order of 1/2 watt are necessary to meet the design goals of the miniature source so that efficiencies $\geqq$ 10% are necessary. With the low gain of these lasers, prospects for this phase of the laser operation are low. Xenon will be used in the laser gas fill, but this will not result in a sufficient lowering of the power consumption to make a significant difference.

The use of Max-R rear reflectors is important for the operation of the small lasers. Gold has a reflectivity on the order of 98% and on several occasions has resulted in failure of the units to lase. Deterioration of the mirrors in the laser medium has seriously hindered the operation of these lasers. In turn, laser action has not been observed in the small lasers for output mirror reflectivities $\leqq$ 95%.

In the small CO_2 lasers, the possibility of using a 98% reflective mirror at each end of the laser has been considered. One mirror can be mounted on a Pz element for laser stabilization. The output from one mirror will be the useful signal output while the output from the second mirror will serve as the signal for controlling the laser. The loss of laser action when a Max-R reflector is not employed has seriously hindered operating in the manner discussed here.

(b) Room Temperature Detectors

Calculations performed during the program (Appendix I) indicate that arrays of room temperature detectors are capable of detecting the Lamb dip in the 4.3 μm fluorescence of CO_2 to serve as a control signal for the molecular frequency source. With the PbSe arrays available toward the end of the contract, conclusive evaluation of these units was not possible. The 4.3 μm fluorescence was observed with the detectors, but the Lamb dip was not evident in these observations. Laser power levels which were employed were low, and continued investigations at higher power levels are necessary to establish if the saturation effect is observable with these detectors.

As indicated previously, a more favorable detector array configuration can result in lower detector bias voltage, and this is a necessity for operation of the miniature source at low power consumption. Improved room temperature detector materials would contribute significantly to the success of the system. PbSe is the best material available for 4.3 μm operation. Time did not permit the investigation of optimization of the collection optics for the 4.3 μm radiation, although this is an important subject which can improve the detector situation.

(c) External Frequency Modulator

The program has reviewed several schemes for an external frequency modulator, all of which are capable of causing the necessary frequency deviation required for locking the laser. For the molecular frequency source, however, all these modulators are too massive and consume larger power than desired.

Electro-optic and Doppler dither techniques have been explored. The latter technique has been successfully employed for saturation studies of SF_6 at 10.6 μm in a cell external to the laser [4] and demonstrated the advantages of the external modulation as removing the dependence of the inverted Lamb dip position on the laser characteristics in addition to eliminating sidebands of the laser. The Doppler dither methods which were examined during the program are capable of the low power consuming modulation necessary if the instability of their motions can be eliminated. The scanning mirror version of this technique, in turn, needs further investigations of the shaping of the stepped mirror in order to be a workable device.

The use of an electro-optic modulator has been determined to be inappropriate because of the limitations imposed by the power consumption. However, Freed has demonstrated that locking can be maintained while extremely small modulation is applied to the laser. In some cases, it was possible to reduce the modulation amplitude to less than 1 kHz. Several points can be raised on the basis of the modulation effects as shown by Freed. If one can operate with a frequency deviation of only 1 kHz with a modulation frequency of 600 Hz, the required electric field for a CdTe phase modulator is approximately 12×10^3 volts/cm. For a 0.3 cm crystal, this corresponds to a voltage of 3600 volts. This approaches the realm of feasible modulators. Depending upon the limit to which the modulation amplitude can be lowered below 1 kHz while still maintaining a lock, this voltage might be further reduced. The upper limit of the modulation frequency must, in turn, be established; Freed found that, at 1 kHz modulation frequency, no signal was observed. It must be emphasized that, in order to maintain lock at the low frequency deviation, the system was already locked at a high frequency deviation from which the modulation amplitude was reduced. A scheme for initiating lock would have to be available before the operation with frequency deviation on the order of 1 kHz can be performed.

While the conventional size electro-optic modulator is restricted in its use by power requirements, recent advances in waveguide electro-optic modulators have indicated that a reduction of more than an order of magnitude in electro-optic modulator drive power requirements is possible at 10.6 μm with the waveguide techniques. The problem of coupling into and out of the modulator, however, is a formidable one for the low power levels at which we must operate.

The use of a stepped germanium plate moved perpendicular to the laser path has been considered as an alternate for a modulator. To go from an air path at a 200 Hz rate requires a Ge plate only 0.63×10^{-2} cm thick. A stepped Ge plate would require a step on the order of 1.5 mm to modulate on the order of 200 Hz. Several similar techniques, some of which employ rotating plates, have been utilized in modulation spectroscopy [5].

In summary, the external modulation situation for miniature molecular sources is that there are several techniques that can provide adequate frequency modulation, but problems in size, stability and power consumption must be solved.

(d) External Fluorescence Control Cell

The external control cells which have been employed thus far consist of a single reflection so that the signal passes through the cell only twice in setting up the standing-wave required for the Lamb dip. Since a volume of gas sufficient to provide a strong signal at a specified vapor pressure is required, the external cell must be sufficiently large. Fabry-Perot interferometers for the CO_2 control gas have been considered, and these devices look promising. The interferometer will provide a multiple-pass system capable of maintaining the standing wave alignment. Difficulty has been experienced in maintaining an optimum alignment with the single reflection apparatus.

In addition to the linear source configuration which has been assembled, an aluminum platform is available to determine the position of components in the folded arrangement shown in Figure 7 of the Second Interim Report. It is laid out so that the laser, collimator and control cell can be inserted as they are developed. The Optical Scanner and stepped mirror can be mounted in the system. This set-up does make the stabilization system larger than desired, having a volume of approximately 40 in^3. The power supplies and electronics are not included in these values. When the final voltage and current requirements are established for the small CO_2 lasers, miniaturized circuits exist for use with these systems.

Of all systems which have been considered for stabilizing the CO_2 laser, the Freed-Javan technique is the most suitable for miniature molecular source systems. The technique does, by far, show the greatest capability for a high degree of stability. Recent investigation of the use of Stark cell stabilization of CO_2 lasers [6] provides a means of stabilizing waveguide lasers. The technique does not require an external modulator other than the dither placed upon the external Stark cell. It is very appropriate for small systems using waveguide lasers, but it has the draw-back of not being capable of high stability, probably on the order of 3 parts in 10^9 long-term, because of the high pressure at which the Stark cell must be operated.

The work performed in this initial investigation of miniature molecular frequency sources has provided a basis for determining the limitations of such systems and for determining those problem areas upon which the greatest emphasis must be placed in the future. Many options must still be evaluated for the various components. As indicated in Appendix I, improved room temperature detectors are an important factor in achieving the required signal-to-noise ratio required for high laser stability. Thermoelectrically cooled PbSeTe detectors, currently under development by the Night Vision Laboratory, will require only one watt input power for operation and have detectivities on the order of 5×10^{10} cm $Hz^{1/2}W^{-1}$.

In this section, the requirements on the individual components of the system have been discussed. It can be concluded that a miniature frequency source can be developed when further research in these areas is performed.

11. References

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APPENDIX I

CALCULATION OF 4.3 μm FLUORESCENCE AT ROOM TEMPERATURE

Freed and Javan [1] have shown that the 4.3 μm fluorescence from a CO_2 cell placed within a 10.6 μm CO_2 laser resonator exhibits the standing wave saturation resonance when the laser is oscillating on a single rotation-vibration transition. Figure I-1 shows the CO_2 energy levels involved. The laser transition occurs between the states (00°1) and (10°0) while the 4.3 μm fluorescence results from the transition from the state (00°1) to the (000) ground state. The 4.3 μm signal arises from transitions from all rotational states of the (00°1) vibrational level and is used as the control signal for stabilizing the laser. The derivative of this signal is obtained by applying a small frequency modulation voltage on the piezo-electric tuner of the laser or by frequency modulating externally. The 4.3 μm derivative signal is used in an automatic feedback control to stabilize the laser frequency at the line profile centers of the various absorbing transitions. A 77°K InSb detector has been employed to observe the 4.3 μm signal.

The detection of the 4.3 μm fluorescence signal must be performed at room temperature for the miniature molecular frequency source. In order to observe the fluorescence with a 298°K detector, compensation must be made for the low detectivity of the room temperature devices by taking advantage of the possibility of using large detector areas or of optimizing the collection optics.

Several detector configurations can be postulated. However, before discussing possible detector configurations, an estimate of the radiated 4.3 μm fluorescence is necessary. A rough estimate of this radiation can be obtained by considering the fluorescent power radiated from a volume V of molecular CO_2:

$$P_F = (N_2 - N_2^{\,o}) \frac{h\nu V}{t_{spont}} \tag{I-1}$$

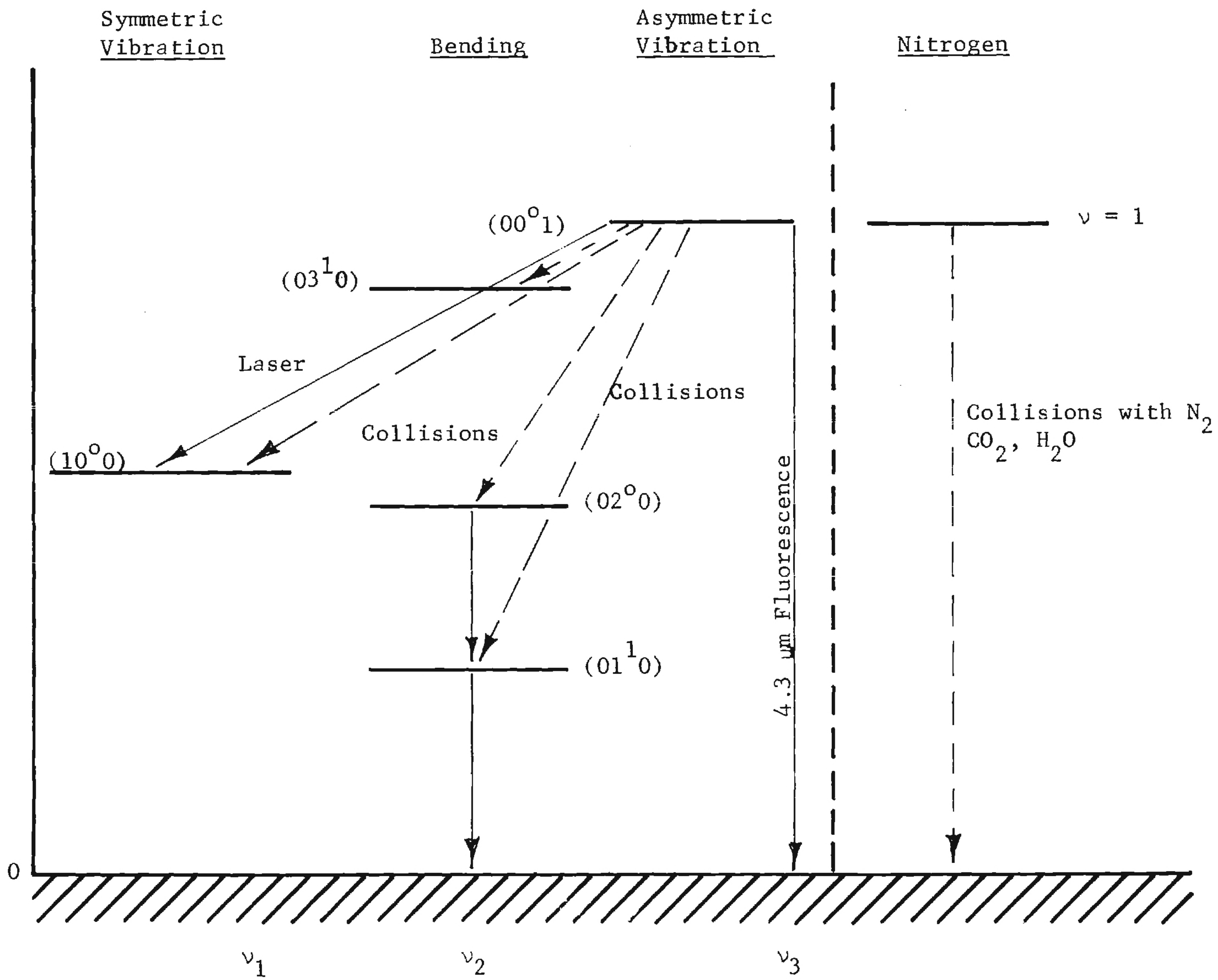

Figure I-1. CO_2-N_2 Energy Level Configuration.

where N_2 is the population of the state 00^o1 under saturation and N_2^o is the population of the same state under thermal equilibrium at 298°K. The spontaneous transition probability $A_{00^o1 \rightarrow 00^o0} = 1/t_{spont}$ is taken as 2×10^2/sec [2] and $h\nu$ is the photon energy at 4.3 μm.

The population N_2 is obtained by considering the population of the two laser levels (10^o0) and (00^o1). For the P(20) laser transition, the populations of the 10^o0, J = 20 and 00^o1, J = 19 are required. The molecular density at 300°K and 0.050 torr is 1.768×10^{15} molecules/cm^3. The fraction of molecules in the (10^o0) vibrational level is $e^{-E_\nu/kT} = 1.29 \times 10^{-3}$. The fraction of these molecules in the J^{th} rotational level is

$$N_J/N = \frac{2hcB}{kT} g_J \cdot \exp\left[\frac{-hcB\ J(J+1)}{kT}\right] \qquad \text{(I-2)}$$

where $g_J = 2J + 1$ is the rotational degeneracy, and $B = 0.3897$ cm^{-1} is the rotational constant for the (10^o0) vibrational state. Then, for J = 20, $N_J/N = 0.070$ at T = 298°K.

For the (00^o1) state, the fraction of molecules in the vibrational level is 1.28×10^{-5} of which the fraction in the J = 19 state is 0.072. The total number of molecules/cm^3 at P = 0.050 torr is then:

for 00^o1, J = 19: 1.62×10^9 molecules/cm^3

and

for 10^o0, J = 20: 1.60×10^{11} molecules/cm^3.

The population difference between the two states is

$$\Delta N^o = N_{10^o0,J=20} - N_{00^o1,J=19}$$

$$= 1.58 \times 10^{11} \text{ molecules/cm}^3.$$

At complete saturation, the populations of the two states approach equality, and the excited state molecules are distributed thermally among the rotational levels so that N_2 in Equation (I-1) becomes 7.9×10^{10} molecules/cm^3. The estimated fluorescence power is then

$P_F = 7.35 \times 10^{-7} V$ watts.

For a control cell volume V of 2" x 1" x 1", the total radiated power is 2.41×10^{-5} watts. This number is high; the determination does not consider the pumping power and has assumed complete saturation in the value used for N_2.

A better estimate should be obtained by considering the molecules in the presence of a standing wave. This is the case for the control cell in the laser resonator or in an external resonator. The assumption is made that the gas in the control cell is exposed to the standing wave of the laser. The calculation of the fluorescent output can be performed in a manner recently discussed by Shimoda [3]. If the laser frequency is $\omega/2\pi$ and the center frequency of the line under absorption is $\omega_{ij}/2\pi$, then the relation for Doppler shifted frequencies is $Kv = \omega - \omega_{ij}$ where $K = \omega_{ij}/c$ and v is the velocity component parallel to the resonator axis. The absorbing transition of CO_2 at 10.6 μm is the same transition, $10^0 0$ - $00^0 1$, as the laser transition. For $\omega = \omega_{ij}$, the inverted Lamb dip occurs at 10.6 μm, and a corresponding reduction of output power is manifested in the 4.3 μm fluorescence. The fluorescence power output is determined by calculating the time rate of change of the population of the $00^0 1$ state under saturation of the absorption transition.

Consider the standing wave to consist of two waves traveling in opposite directions. The transition probability in one beam of E cos $(\omega t + Kz)$ is

$$S_1(v) = \frac{x^2}{2} \frac{\gamma}{(\omega - \omega_{ij} - Kv)^2 + \gamma^2} \tag{I-3}$$

where E is the laser electric field,

$x = |\mu_{ij}| E/\hbar$,

$|\mu_{ij}|$ = the dipole moment for the absorption transition,

γ = homogeneous linewidth, and

v = component of molecular velocity along the Z-axis.

For the beam in the opposite direction, $E \cos(\omega t - Kz)$, the transition probability is

$$S_2(v) = \frac{x^2}{2} \frac{\gamma}{(\omega - \omega_{ij} + Kv)^2 + \gamma^2} \tag{I-4}$$

With these relations, the rate equations of molecular populations in levels i and j are:

$$\frac{d}{dt} N_i(v) = -\left\{S_1(v) + S_2(v)\right\}\left\{N_i(v) - N_j(v)\right\} - \frac{(N_i(v) - N_i^o(v))}{\tau_i} \tag{I-5}$$

and

$$\frac{d}{dt} N_j(v) = \left\{S_1(v) + S_2(v)\right\}\left\{N_i(v) - N_j(v)\right\} - \frac{(N_j(v) - N_j^o(v))}{\tau_j} \tag{I-6}$$

with N_i^o and N_j^o = values in absence of laser radiation, and τ_i, τ_j = lifetimes of levels i and j.

The steady state solution gives the population difference

$$\Delta N(v) = N_i(v) - N_j(v) = \frac{\Delta N^o(v)}{1 + 2\tau\left\{S_1(v) + S_2(v)\right\}} \tag{I-7}$$

where $\tau = \frac{\tau_i + \tau_j}{2}$, and

$$\Delta N^o(v) = N_i^o(v) - N_j^o(v) \; .$$

Maxwell's velocity distribution holds so that

$$\Delta N^o(v) = \frac{\Delta N^o}{\sqrt{\pi}\, u} \exp \frac{-v^2}{u^2} \tag{I-8}$$

where u = the most probable velocity of CO_2 at T = 300°K and ΔN^o is the difference in population of the laser energy levels without the exciting field applied.

For the nonlinear part of the fluorescence, the number of molecules excited per unit time is obtained from the rate equations and the above steady state solution:

$$\frac{dn}{dt} = V \int_{-\infty}^{\infty} \frac{\{S_1(v) + S_2(v)\} \ \Delta N^o(v)dv}{1 + 2\tau \ \{S_1(v) + S_2(v)\}} \ . \qquad \text{(I-9)}$$

The observable power of fluorescence in the solid angle Ω_F is then given by

$$P_F = \frac{\Omega_F}{4\pi} \eta_F \hbar \omega_F \frac{dn}{dt} \qquad \text{(I-10)}$$

where η_F = fluorescence quantum efficiency and $\hbar \omega_F$ = energy of fluorescence photons.

In order to evaluate the integral in the vicinity of the absorption peak ($\omega \approx \omega_{ij}$), it is reasonable to assume $S_1(v) \approx S_2(v)$ so that

$$\begin{aligned} \frac{dn}{dt} &= \frac{V\Delta N^o}{\sqrt{\pi}\, u} \int_{-\infty}^{\infty} \left(\frac{S_1(v)}{1 + 4\tau \ S_1(v)} + \frac{S_2(v)}{1 + 4\tau \ S_2(v)} \right) dv \\ &= \frac{V\Delta N^o x^2 \gamma}{2\sqrt{\pi}\, u} \left\{ \int_{-\infty}^{\infty} \frac{dv}{(\omega - \omega_{ij} + Kv)^2 + \gamma^2 + 2\gamma x^2 \tau} \right. \\ &\quad \left. + \int_{-\infty}^{\infty} \frac{dv}{(\omega - \omega_{ij} - Kv)^2 + \gamma^2 + 2\gamma x^2 \tau} \right\} . \end{aligned} \qquad \text{(I-11)}$$

Let $\Delta\omega^2 = \gamma^2 + 2\gamma x^2 \tau$ and use the integral

$$\int \frac{dx}{(a + bx)^2 + c^2} = \frac{1}{bc} \tan^{-1} \frac{x}{c} \ .$$

The resulting expression for dn/dt becomes

$$\frac{dn}{dt} = \frac{V\Delta N^o \; x^2 \; \gamma \; 2\sqrt{\pi}}{Ku\Delta\omega} \tag{I-12}$$

for $\omega \approx \omega_{ij}$.

For a laser with approximately 50 mW output, about 25 mW will reach the control cell. This power will be expanded to fill the 1/2 inch diameter control cell. Under these conditions, the intensity is 204 watts per $(\text{meter})^2$. This corresponds to $E^2 = 15.36 \times 10^4 \ (\text{V/m})^2$ since

$$I = \frac{\varepsilon_o c \; E^2}{2} \ \text{watts}/(\text{meter})^2$$

where $\varepsilon_o = 8.854 \times 10^{-12}$ Farads/m and c is the velocity of light. That this is sufficient input power to the control cell to result in detectable saturated 4.3 μm fluorescence can be seen from the following:

The fluorescence power at 4.3 μm will take the form

$$P_F = \frac{2\Omega_F \; \eta_F \; \hbar \; \omega_F \; V\Delta N^o \; x^2 \; \gamma \; \sqrt{\pi}}{4\pi \; Ku\Delta\omega} \quad . \tag{I-13}$$

To evaluate this expression, the following parameters are available from the experimental configuration:

V = volume of gas,

$\Delta N^o = N_i^{\ o} - N_j^{\ o}$ (molecules/cm^3),

$x^2 = \dfrac{|\mu_{ij}|^2 \; E^2}{\hbar^2}$ (units of Hz^2),

γ = homogeneous linewidth in Hz $\approx$ 0.33 MHz,

$K = \dfrac{\omega_{ij}}{c} = \dfrac{2\pi\nu_{ij}}{c} = 0.593 \times 10^4 \ \text{cm}^{-1}$ for 10.6 μm radiation,

$\hbar = 1.0545 \times 10^{-34}$ joule seconds,

$\omega_F = 4.384 \times 10^{14}$ radians/sec for the 4.3 μm fluorescence, and

$u = \sqrt{\dfrac{2kT}{m}} = 3.3549 \times 10^4$ cm/sec for CO_2.

Calculating x^2 from the electric field corresponding to 25 mW from the laser yields

$$x^2 = 1.55 \times 10^{14} \ (\mathrm{Hz})^2$$

Under conditions of saturation, $x^2 \sim \gamma/2\tau$, then $\Delta\omega^2 = 2\gamma^2$ so that the fluorescence power is given by

$$P_F = 2.32 \times 10^{-29} \ \Omega_F \ \eta_F \ \frac{V\Delta N^\circ \gamma}{\tau} \tag{I-14}$$

For $\gamma \approx 0.33 \times 10^6$ Hz, $P_F = 7.66 \times 10^{-24} \ \Omega_F \ \eta_F \ \frac{V\Delta N^\circ}{\tau}$. (I-15)

Data exist for the lifetimes of the states $10^\circ 0$ and $00^\circ 1$ of CO_2 at low pressures. The work of Cheo [4] gives the values

$$\tau_{10^\circ 0} \approx 10^{-4} \ \mathrm{sec}$$

and

$$\tau_{00^\circ 1} \approx 10^{-3} \ \mathrm{sec}$$

so that

$$\tau = 0.55 \times 10^{-3} \ \mathrm{sec}.$$

The population difference for a control cell of CO_2 at 50 millitorr was shown above to be

$$\Delta N^\circ = 1.58 \times 10^{11} \ \mathrm{molecules/cm^3}$$

so that

$$P_F = 2.2 \times 10^{-9} \ \Omega_F \ \eta_F \ V \ \mathrm{watts} \ .$$

At the time of this calculation, we did not have available a value for the fluorescence quantum efficiency. If only radiative processes are considered, an estimate can be made from the transition probabilities [2]. The value used is $\eta_F = 0.75$ for the $00^\circ 1 \rightarrow 000$ transition. It is possible that this value is high. Then,

$$P_F = 1.65 \times 10^{-9} \ \Omega_F \ V \ \mathrm{watts}.$$

The fluorescence power output is seen to be a function of the gas volume (V) and the observation configuration or solid angle.

Consider the case of an external resonator containing CO_2 at a pressure of 50 millitorr. If the resonator volume which is illuminated with the laser radiation is 1 inch x 1 inch x 2 inches, or 32.8 cm^3, the power output is

$$P_F = 5.41 \times 10^{-8} \ \Omega_F .$$

For the use of 298°K detectors, consideration must be given to an array of PbSe detectors surrounding the control cell resonator.

If one considers 24 detectors of 1.25 cm x 1.25 cm area which would be placed on the four sides of the cell, an estimate of the observation angle Ω_F can be made by excluding the equivalent of one end plate. A conservative estimate sets Ω_F at 80% of 4π or approximately 10 steradians so that the total output power at 4.3 μm is

$$P_F \approx 5.41 \times 10^{-7} \text{ watts}$$

or

$$2.25 \times 10^{-8} \text{ watts per detector}$$

if it is assumed that the power is uniformly distributed over the 24 detectors.

For infrared detectors, an indication of the sensitivity of a detector is given by

$$D^*(\pi) = \frac{\sqrt{AB}}{NEP} \ \frac{\text{cm Hz}^{1/2}}{\text{watts}} , \tag{I-16}$$

where A is the detector area and B is the bandwidth of the post-detector amplifier. NEP is the noise equivalent power, i.e., the minimum detectable power required to produce a S/N = 1. In the case of PbSe, $D^*(\pi) \approx 1 - 2 \times 10^9$ cm $Hz^{1/2}$/watts, so that, for detectors with $\sqrt{A} \approx 1.25$ cm, NEP $\approx 10^{-9}$ watts. Since the noise varies as the square root of the area, the total noise power for the 24 detectors is expected to be approximately 4.9×10^{-9} watts.

The signal-to-noise ratio is then on the order of 110. This is S/N for the CW power emitted at 4.3 μm with no account being taken of modulation.

In order to obtain an indication of the S/N to be expected at the modulation frequency, a comparison can be made with the system which has used a 77°K InSb detector [1] with a control cell within the laser resonator. If it is assumed that a 9 mm bore laser tube is used and that approximately 1.3 cm length of the tube is observed, then the gas volume under observation is approximately 0.82 cm^3. With the detector placed approximately 1.5 cm above the control cell, $\Omega = \pi \sin^2 \theta/2 \approx 0.497$ steradians. The angle $\theta/2$ is the half-angle of the observation cone. This yields a fluorescence power output of 9.31×10^{-8} watts. For InSb, $D^*(\pi) \approx 6 \times 10^{10}$ cm $(Hz)^{1/2}$/watt. For a cone angle of θ, $D^*(\theta) = \frac{1}{\sin \theta/2} D^*(\pi) = 1.35 \times 10^{11}$ for the case considered here. The NEP for a 2 mm x 2 mm detector element is 1.48×10^{-12} watts so that $S/N \simeq 453$. The experimental S/N at the modulation frequency [1] is approximately 15 for an integration time on the order of 1 sec. On this basis, $S/N \approx 4$ can be expected with the room temperature array.

Because of the assumptions made in the evaluation of the integral in Equation (I-11), the fluorescence power, as given in Equation (I-13), does not include the frequency dependence of the Lamb dip. In order to show this dependence, the factor

$$\left[1 - \frac{\tau x^2}{2\gamma} \left\{1 + \frac{\gamma^2}{(\omega - \omega_o)^2 + \gamma^2}\right\}\right] \exp\left[-\left(\frac{\Omega}{Ku}\right)^2\right]$$

must be included. Here, $\Omega = \omega - \omega_o$.

In order to obtain the component at the synchronous detector frequency, which would constitute the error signal used to correct the laser, we can follow the calculations employed in atomic beam determinations [5]. The fluorescence response for small departures from the dip center can be approximated as

$$P_f(t) = A - \frac{P_f^{\circ}}{2} \left[1 + \cos \pi \left(\frac{\Delta\omega(\tau)}{\omega_\ell}\right)\right]$$

where $P_f{}^\circ$ is the peak-to-valley of the Lamb dip, A is the amplitude of the fluorescence without the dip, $\Delta\omega(\tau)$ is the departure from line center and ω_ℓ is the full dip width. The factor $P_f{}^\circ$ can be expressed in terms of the power output P_F given above, since $P_F = A - P_f{}^\circ$. If the dip is approximately 20% of the amplitude, then $P_f = 0.25\ P_F$. Let $\Delta\omega(\tau)/\omega_\ell = \varepsilon + \alpha \cos \omega_m \tau$ to allow for sinusoidal modulation, where ω_m is the modulation frequency assumed small in comparison with ω_ℓ and α is the modulation amplitude. It has been shown [5] that the result of synchronous detection of this signal is

$$P_f = P_f{}^\circ\ J_1(\pi\alpha)\ \frac{\sin \pi\varepsilon}{2}$$

$$\approx \frac{P_f{}^\circ\ J_1(\pi\alpha)}{2}\ \pi\varepsilon$$

for small ε, the fractional detuning. For a given offset, ε, this has the absolute value of $0.91\varepsilon\ P_f{}^\circ$ for $\pi\alpha \approx 1.8$, the first maximum of the Bessel's function. This is then the lock-in signal output. If we let $P_f{}^\circ = 0.25\ P_F$, then

$$P_f \approx 0.23\varepsilon\ P_F\ .$$

For a fractional detuning $\varepsilon = 0.1$ then $P_f \approx 0.023\ P_F$. For the total output power $P_F \approx 5.41 \times 10^{-7}$ watts, we can consider using the four detectors in Table 2 with the highest detectivities. The total noise for these detectors in a 1 Hz bandwidth is 0.41 μV and the average responsivity is 87 V/W. Then $P_f \approx 1.24 \times 10^{-8}$ watts, and the voltage signal output is 1.08 μV for a signal-to-noise ratio of 2.7.

This calculated S/N is lower than is desirable; however, the calculations depend on several assumptions, the validity of which must still be determined. The condition for saturation, $x^2 = \delta/2\tau$, has been employed. A higher input power would increase the signal-to-noise ratio but would, in turn, broaden the line. The fractional detuning $\varepsilon \approx 0.1$ represents a detuning of 3×10^4 Hz so that, for the CO_2 laser transition of approximately 3×10^{13} Hz, this corresponds to a change in frequency by a part in 10^9 before the $S/N \approx 3$. Improvement in room temperature detectors is a necessary part of the investigation to achieve high stability; however, the Lamb dip derivative should be observable with the existing detectors.

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